ISSN:2231-0711

Jaswanth Bhargav Padigala et al | IJCSET |August 2013 | Vol 3, Issue 8, 273-278

A Review of QoS in Wireless Sensor Networks

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***Abstract* —The adoption of wireless sensor networks by applications that require complex operations, ranging from health care to industrial monitoring, has brought forward a new challenge of fulfilling the quality of service (QoS) requirements of these applications. However, providing QoS support is a challenging issue due to highly resource constrained nature of sensor nodes, unreliable wireless links and harsh operation environments. In this paper, we focus on the QoS support at the MAC layer which forms the basis of communication stack and**
has the ability to tune key QoS-specific parameters, such as duty cycle of the sensor devices. We explore QoS challenges and perspectives for wireless sensor networks, survey the QoS mechanisms and classify the state of the art QoS-aware MAC protocols together with discussing their advantages and disadvantages.

***Keywords* —** QoS, QoS challenges, QoS perspectives, QoS mechanisms, Priority assignment, Service differentiation mechanisms, Wireless sensor networks ,MAC layer, QoS-aware MAC protocols.

1. INTRODUCTION

Wireless sensor networks (WSNs) have appeared as one of the emerging technologies that combine automated sensing, embedded computing and wireless networking into tiny embedded devices. While the early research on WSNs has mainly focused on monitoring applications, such as agriculture [1] and environmental monitoring [2], based on low-rate data collection, current WSN applications can support more complex operations ranging from health care [3] to industrial monitoring and automation [4]. Besides these, the availability of low-cost hardware and rapid development of tiny cameras and microphones have enabled a new class of WSNs: multimedia or visual wireless sensor networks [5,6] and this new class has contributed to new potential WSN applications, such as surveillance.

What is common in these emerging application domains is that performance and quality of service (QoS) assurances are becoming crucial as opposed to the best-effort performance in traditional monitoring applications. The term QoS is widely used in the area of all kinds of networks but still there is no consensus on its exact meaning. International Telecommunication Union (ITU) Recommendation E.800 (09/08) has defined QoS as: ‘‘Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service’’. Traditionally it refers to the control mechanisms that orchestrate the resource reservation rather than the provided service quality itself. Simply or practically, QoS brings the ability of giving different priorities to various users, applications, and data flows, frames or packets based on their requirements by controlling the resource sharing. Hence higher level of performance over others can be provided through a set of measurable service parameters such as delay, jitter, available bandwidth, and packet loss.

QoS requirements in traditional data networks fundamentally stem from the end-to-end bandwidth-hungry multimedia applications [7]. In this context, reservation based approaches, such as Integrated Services or IntServ [8], are widely used in providing QoS guarantees. However, guaranteeing a certain QoS is a challenging issue due to the unpredictable nature of the wireless links, unstable topology (due to node failure or link failure) and severe resource constraints in WSNs. These constraints make it harder to adopt the existing solutions in wired and other wireless networks. Besides these constraints, while recent applications, especially real-time, multimedia and mission-critical applications, call for Qos support, the inherent characteristic of WSNs, ‘‘energy efficiency’’ makes the QoS provision a challenging task. Parallel to recent advancements, WSN applications have become more and more bandwidth-hungry and delay sensitive. In order to meet these requirements, WSNs need novel and well-designed QoS support in each layer of the communication protocol stack since envisioned applications are dissimilar to traditional end-to-end applications. Especially real-time multimedia and mission-critical applications brought forward new QoS requirements since they need delay-bounded and reliable data delivery. This variety of the applications and requirements of these applications make implementation of a ‘‘one-size-for-all’’ QoS-support mechanism impossible. However, well-defined requirements and QoS parameters can be a guide to develop QoS-support for effective and efficient delivery of sensor data. In this work, we focus on the QoS support at the MAC layer and survey the existing protocols in the literature.

Although centralized MAC schemes exist for other types of networks, such as point coordination function (PCF) in IEEE 802.11, where nodes request the right for medium access from a coordinator, these schemes are hardly applied to WSNs due to the large number of sensor nodes, multi hop nature of the networks and scalability issues. Therefore, our focus is on distributed QoS support at the MAC layer. The reason why we focus on the MAC layer is that, all other upper-layer components are dependent on the MAC layer and this makes it a primary decisive factor for the overall performance of the network. Nowadays, cross-layer solutions for WSNs where functionalities of multiple traditional layers are melted into a functional module, are widely adopted [9]. By the cross-layer approach, a single module can obtain every necessary information regardless of the layer abstraction and has chance to optimize the overall performance of the sensor network. However, interoperability or interchangeability between layers cannot be mentioned in this case since there is no layer abstraction within the protocol stack. In case of QoS support, there is no distinction between layered and cross-layer protocols. QoS awareness can be adopted with the same goals and challenges by both concepts. In this paper, our aim is to survey the existing QoS aware MAC protocols for WSNs including mobile, underground and underwater sensor networks. To the best of our knowledge, although there exist surveys on QoS support in WSNs [7] and on MAC protocols for WSNs [10,11], there is no extensive survey paper on the QoS aware MAC protocols, including their comparative evaluation. Although, Zogovic et al. [12] briefly summarize QoS Provisioning at MAC and physical layers for WSNs, they neither provide an extensive survey, nor discuss the comparisons and provide a classification together with future research directions. Our contribution is to present a detailed survey on the topic and discuss the open issues in this domain which, we believe, is going to receive a lot of attention in the coming years. We start with a background information in the context of QoS provision in wired and wireless networks. We summarize different types of QoS approaches and discuss which can be applied to WSNs. Additionally, we mention the QoS perspectives, namely application-specific QoS and network-specific QoS, and discuss the requirements of different types of applications. Then, we elaborate on the challenges of QoS provisioning in WSNs and discuss the QoS metrics, such as bounded delay, guaranteed throughput, together with the tunable parameters at the MAC layer, such as duty cycle, contention window size. After explaining the metrics and parameters, we discuss the QoS mechanisms that can be applied in the context of WSNs. We then continue explaining the details of existing QoS-aware MAC protocols for WSNs including their QoS metrics, parameters, mechanisms and present an extensive comparison of them. We conclude the paper with open research issues and possible future research directions. The rest of the paper is organized as follows: in Section 2, we provide background information on QoS support in wired and wireless networks. In Section 3, we discuss the QoS challenges and continue with the QoS metrics in WSNs in Section 4. We present the QoS mechanisms in Section 5 and explain the details of the existing QoS-aware MAC protocols in WSNs and give comparisons in Section 6. Section 7 discusses the MAC layer tradeoffs and Section 8 elaborates on the properties of a well-defined MAC protocol. In Section 9 we discuss the open issues and give possible directions for the future research. Finally, in Section 10, we draw the conclusions.

2. BACKGROUND AND QOS PERSPECTIVE

Internet was initially designed for providing the best effort delivery of application data since average performance guarantees were sufficient for initial types of applications [13]. However, with the emergence of applications, such as Internet telephony and video streaming, that require high throughput, bounded delay, bounded delay jitter, and high reliability, best effort delivery has become insufficient to support these applications. Consequently, this has driven and enabled the development of algorithms, protocols and mechanisms that provide QoS support for diverse set of applications. A similar situation is currently observed in WSNs. Traditionally, WSNs have been used for monitoring applications based on low-rate data collection with low periods of operation. Current WSNs are considered to support more complex operations ranging from target tracking [14] to assisted living [15] which require efficient, reliable and timely collection of large amounts of data. Moreover, the recent advances in image sensor technology, have enabled the use of video sensors and this resulted in a new class of WSNs, called visual or multimedia sensor networks [5,6], that can be used for various potential applications, such as tele-presence and surveillance. It is certain that, these networks also have tighter QoS requirements, such as low data delay and maximum reliability, compared to traditional WSNs [6].

2.1. QoS provisioning and service differentiation in traditional Networks:

Shortly, QoS is the ability of a network to satisfy the certain requirements of the user or application. There are two main types of QoS provision defined in wired and wireless networks: Hard QoS and Soft QoS. The applications that require hard QoS should be provided deterministic QoS guarantees, such as strict bounds on packet delays, bandwidth or packet losses. In soft QoS approach, again the application has tight QoS requirements but the temporal violations on QoS provisioning can be tolerated to a certain extent [13]. Service differentiation is the widely adopted scheme in both wired and wireless networks to provide hard/soft QoS guarantees. There are two service differentiation models proposed for conventional computer networks, Integrated services (IntServ) [8] and differentiated services (DiffServ) [16]. Aim of both the differentiation models are to prioritize flows or packets, map their priorities into service qualities and provide required service quality by sharing limited resources among them. IntServ model maintains service on a per-flow basis and can be considered as a reservation-based approach. It specifies a fine grained QoS system and follows the hard QoS approach [17]. Flows can be considered as data-centric or host-centric where data-centric consideration can be information generated by motion sensors from a commonly used breach path in border surveillance and host-centric consideration can be the stream of packets between a particular source and destination. However, IntServ model has a number of disadvantages which makes it inappropriate for WSNs. Firstly, it is hard to provide guaranteed service quality due to time varying channel capacity on the wireless medium. Second, maintenance of the per-flow states of the sensor nodes and scalability for dense networks is a real challenge. Third, IntServ model requires a reliable in-band or out-of-band QoS signaling within the sensor network for resource reservation which is very hard to assure in WSNs. DiffServ model maintains service on a per-packet basis and can be considered as a reservation-less approach. Major drawback of DiffServ model is its costly memory requirement since every network entity will behave as a source and an intermediate hop. However, lightweight and easy-to-implement DiffServ model can be adapted to WSNs easily and this model operates in a multi-hop manner [18]. Each packet will have a degree of importance and this will be apparent for every entity of the network. In this way, each layer of the communication protocol stack can treat the packet by the way its priority imposes. Therefore, DiffServ model will be assumed as the default service differentiation method for the rest of our work.

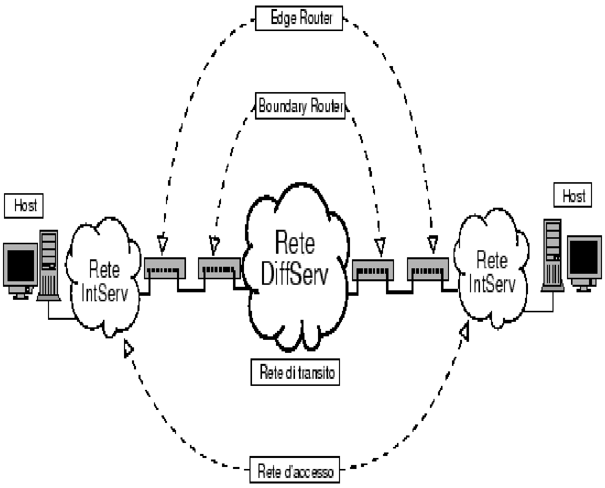

Fig. 1. Network-specific QoS model with IntServ and DiffServ.

Fig. 1 shows the concepts of IntServ and DiffServ models discussed in this section.

2.2. QoS perspectives in WSNs:

QoS perspective actually defines the aspect of QoS which we are interested. In an earlier work [7], Chen et al. classified the QoS perspectives in WSNs into two categories as Application-specific and Network-specific. These two perspectives represent the two different approaches already followed in the literature:

- Application-specific perspective: Application-specific perspective focuses on the quality of the application itself. QoS is again assured by fulfilling the requirements imposed by the application such as lifetime [19,20], coverage [21], deployment, quality of the sensing, camera resolution, number of active sensors [22,23].
- Network-specific perspective: Network-specific perspective provides service quality during delivery of the data by the communication network. From this perspective, network resources are utilized efficiently in each layer of the communication protocol stack to fulfill the requirements imposed by the carried data, such as latency, packet loss, reliability. In this paper, since our focus is on QoS-aware MAC protocols, we will be approaching from the network-specific perspective to QoS provisioning and hence, application specific perspective will be out of our scope in this work. The reader can refer to [7,19–23] for the application specific approaches.

2.3. QoS support at MAC layer:

Although collective effort of all the communication protocol stack entities is essential for QoS provisioning, MAC layer possesses a particular importance among them since it rules the sharing of the medium and all other upper layer protocols are bound to that. 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. Besides, the MAC layer handles the additional challenges of the WSNs such as severe energy constraints by duty cycling and unpredictable environmental conditions by methods such as retransmissions or transmission power control. Therefore, the MAC layer plays a key role for QoS provisioning and dominates the performance of the QoS support. The reader can refer to [24 – 29] for QoS support at the network layer, and to [30 – 33] at the transport layer and to [34] for different layers.

3. QOS REQUIREMENTS, METRICS AND PARAMETERS

In this section, we first highlight the QoS requirements in WSNs from the perspective of the requirements of different data collection models [46]. Next, we focus on the metrics and parameters to be tuned for QoS provisioning.

3.1. Qos requirements:

Although our focus is on network-specific QoS in WSNs, as we mentioned in Section 2.2, QoS requirements of different applications differ from each other. For instance, traditional low-rate data collection applications may tolerate delay and jitter but packet losses may be important for the application whereas high rate, real time applications, such as target tracking, require a bound on the maximum acceptable delay. Therefore, application requirements are also important for network-specific QoS. Rather than investigating the QoS requirements of every application in WSNs, it is a better approach to focus on the data delivery models that are used in different applications and map the requirements of these data collection models to a set of QoS metrics. This approach was also followed in [7]. Depending on the application requirements, there are three basic data delivery models: continuous, query driven, and event-driven model [46]. In the following part, we discuss these models and their associated QoS requirements:

1. Event-driven: In this model, sensor nodes report data only if an event of interest occurs. Usually, the events are rare. Yet, when an event occurs, a burst of packets are often generated that need to be transported reliably, and usually in real-time, to a base station. The success of the network depends on the efficient detection and notification of the event that is of interest to the user. This is bound to quality and accuracy of the observation related to the observed phenomena with reliable and fast delivery of the information about the detected event. Since more than one sensor nodes will detect the event and generate related data, this type of applications are not end-to-end. Also creation of highly redundant and bursty traffic by sensors affected by the same event is very likely to be observed in event driven applications. Surveillance and target tracking can be an example for this class.

2. Query-driven: Query-driven data delivery model is very similar to the event-driven model with an exception: Data is pushed to the sink without any demand by the sensor nodes in event-driven model while data is requested by the sink and pushed by the sensor nodes in the query-driven model. Hence, contrary to the one-way traffic of event-driven model, two-way traffic comes into scene which consists of requests of the sink and replies of the sensor nodes. Both

requests and replies must be delivered quickly and reliably for achieving higher performance in query-driven applications. Environmental control or habitat monitoring can be an example for this class.

3. Continuous: In this model, sensor nodes transmit the collected data at periodic intervals and can be considered as the basic model for traditional monitoring applications based on data collection. The data rates can be usually low and to save energy the radios can be turned on only during data transmissions if scalar data is collected. However, real-time data such as voice or image are delay-intolerant and requires a certain level of bandwidth. Also packet losses are tolerated in a limited threshold. For periodically collected non real-time data, latency and packet losses are tolerable. Surveillance or reconnaissance can be an example of this class.

4. Hybrid: If the mentioned data delivery models coexist in the same network, carried traffic must be classified and requirements of these traffic classes must be satisfied. A surveillance application that sends both periodic temperature and event-triggered video data is an example of the hybrid model.

3.2. Qos metrics and parameters:

In the previous subsection, we discussed the QoS requirements of WSNs from the perspective of applications that adopt similar data collection models. In this section, we present the metrics that quantify these QoS requirements. The general metrics from the networking perspective are maximizing throughput and goodput, minimizing delay, maximizing reliability, minimizing delay jitter, maximizing energy efficiency, etc. In order to perform well regarding these metrics, the overall impact of the whole protocol stack should be taken into account while supporting QoS. However, since our focus is on the MAC layer, we focus on the performance metrics that can be fulfilled at the MAC layer, as follows:

- Minimizing medium access delay: It is certain that in order to minimize the end-to-end delay from sensor sources to the sink node, the performance of routing layer should also be taken into account. What can be done at the MAC layer in terms of delay is to minimize the medium access delay of the sensor devices to ensure that the packet latency is optimized to meet the end-to end delay requirements.
- Minimizing collisions: Collisions, and consequently retransmissions, directly impact the overall networking metrics such as throughput, delay and energy efficiency. Since the MAC layer coordinates the sharing of the wireless medium, it is responsible for minimizing the number of collisions. Collisions can be prevented by careful carrier sensing methods, such as adapting contention window according to the traffic requirements, considering the contention-based protocols. Similarly, adapting the number of time slots, frequencies according to network requirements can prevent collisions in the case of contention-free protocols.
- Maximizing reliability: Related with minimizing the collisions, MAC layer can also contribute to reliability assurance. Acknowledgement mechanisms can be used to identify the packet losses and accordingly retransmissions can be performed in time to fix the problems.
- Minimizing energy consumption: Energy efficiency is still the most important requirement in WSNs due to the battery-limited operation of sensor devices. MAC layer can contribute to energy efficiency by minimizing collisions and retransmissions and more importantly can tune the duty cycle of the sensor devices according to the network dynamics. Duty cycling is important in WSN operations since the wireless operation consumes most of the energy and radio should be kept off whenever it is not needed. Moreover, transmission power of the sensor radios can be adapted according to network conditions to minimize energy consumption at the MAC layer.
- Minimizing interference and maximizing concurrency (parallel transmissions): Since wireless medium is a shared medium, all unwanted transmissions within the same network or transmissions from other networks that share the same parts of the spectrum contribute to interference on the intended transmissions. Interference causes packet loses and hence affect the throughput, delay and energy efficiency of the network.

Table 1
Important MAC layer QoS metrics for application classes.

QoS metric	Event driven	Query driven	Cont.	Hybrid
Medium access delay	✔	✔		✔
Collision rate			✔	✔
Reliability	✔	✔		✔
Energy consumption	✔	✔	✔	✔
Interference/concurrency			✔	✔
Adaptivity	✔	✔		✔

4 MAC- LAYER DESIGN TRADEOFFS FOR QOS PROVISIONING

Critical decisions must be taken during the design phase of the protocols. These design tradeoffs need to be studied extensively and must be chosen according to specific requirements of the sensory application since they will provide a basis for the protocol. In this section, we will evaluate MAC layer design tradeoffs and highlight their advantages and disadvantages from the QoS point of view. Most of the design tradeoffs are related with service differentiation since it is an integral part of the QoS provisioning and majority of the MAC layer protocols provide differentiated services.

4.1. *CSMA vs. TDMA schemes*

TDMA scheme divides the time into smaller slots and sensor nodes communicate within their own slots in a contention- free manner. Hence, a centralized or distributed slot assignment algorithm is needed in TDMA to decide which sensor node will transmit its packet in which transmission slot. As a result of this scheduling, wireless channel can be utilized well. Moreover, theoretical QoS bounds such as throughput and latency can be given since each sensor node knows when to transmit. This also brings the ability to easily adopt a sleep-listen schedule for energy saving. However, the scheduling algorithm must have information regarding the number of sensor nodes and their positions in order to make a proper slot assignment. Although some examples of scheduling algorithms require only the information of neighboring sensor nodes, they still require a neighbor discovery operation. Having the topological information of the network or neighbor discovery is not sufficient for slot assignment in the long term. Depletion of energy resources, hardware malfunctioning, node mobility, link failures can cause frequent topology changes in WSNs and up to date state of the network must be obtained periodically for accurate slot assignment. Thus, TDMA does not scale well as the size of the network increases.

On the other hand, contention-based schemes where sensor nodes contend to access the shared medium are very easy to implement and more appropriate for infrastructure-less sensor networks. CSMA scheme does not require any additional information related with the network topology or offered traffic load. Thus, performance of the CSMA schemes are not as dependent as TDMA schemes on the network topology and scales well for changing network size and density. Moreover, contention-based schemes can handle bursty and sporadic traffic since sensor nodes do not have to follow a transmission schedule.

4.2 Static vs. dynamic priority assignment:

Selected priority assignment method is quite important for QoS support since resource sharing among different priority classes is carried out according to their importance. Priorities can be assigned to the sensor nodes as well as to the packets created by them. Assigning the priorities statically is not a complex issue since there is no need for any observation or calculation. Once the priority is given, it does not change during the operation of the sensor node or delivery of the packet. On the other hand, dynamic priority assignment needs some additional assessments and priority reassignment accordingly in every triggering event (e.g. arriving another hop for packets, role changes for sensor nodes) which brings an extra overhead to the QoS mechanism. However, adaptive changes regarding the importance of the packet or the sensor node can significantly improve the performance of the QoS mechanism.

5.OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

Application fields of the WSNs are growing rapidly as the capabilities of the tiny sensor devices improve and these applications mostly require varied types of quality assurance. Moreover, diversity of the applications yields to heterogeneous WSNs composed of multimodal sensor nodes which provide more than one functionality by delivering multiple types of traffic. Therefore, novel MAC protocols which have the ability to fulfill the diverse QoS requirements of heterogeneous sensor networks are required. Heterogeneity of the sensor devices not only introduces challenges but also advantages as well. In recent studies, it is possible to see WSNs composed of several types of sensor devices which have diverse set of capabilities (e.g. energy, communication range, sensing and processing capability). Therefore, envisioned MAC protocols must exploit this diversity in favor of the QoS provisioning by dynamically adapting themselves to the available resources in the sensor device on which they operate.

CONCLUSIONS

Current WSNs are not only used for traditional low data-rate applications but also for more complex operations which require efficient, reliable and timely collection of large amounts of data. Moreover, they are not only composed of sensor devices which generate scalar data but also the use of video and microphone sensors are becoming common. Increasing capacities of the sensor nodes, variety of the application fields and multimodal use of sensors require efficient QoS provisioning mechanisms in WSNs. With these requirements in mind, we have focused on the perspectives, challenges, metrics, parameters and requirements of QoS-aware MAC protocols for WSNs in this paper and surveyed the existing protocols together with their comparisons and classifications.

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