**ANKARA YILDIRIM BEYAZIT UNIVERSITY**

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# A NEW BUFFER MANAGEMENT SOLUTION TO IMPROVE THE PERFORMANCE OF MAC LAYER IN WIRELESS SENSOR NETWORKS

**Ph.D. Thesis by**

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**March, 2019**

**ANKARA**

# A NEW BUFFER MANAGEMENT SOLUTION TO IMPROVE THE PERFORMANCE OF MAC LAYER IN WIRELESS SENSOR NETWORKS

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**by**

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# Ph.D. THESIS EXAMINATION RESULT FORM

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**2019, 10 March** **Derviş AYGÖR**

# A NEW BUFFER MANAGEMENT SOLUTION TO IMPROVE THE PERFORMANCE OF MAC LAYER IN WIRELESS SENSOR NETWORKS

## ABSTRACT

Wireless Sensor Network (WSN) is an autonomous network that detects physical changes in an environment and reports the relevant information to a central point for further investigation. WSNs are an important type of resource-constrained distributed systems. There are many limitations on the sensor nodes such as: energy, memory, computation capability, storage, transmission range and etc. All these limitations make efficiency and effectiveness very important and highly demanded features for WSNs.

In this study, buffer management mechanisms that can be utilized on sensor nodes at different communication layers were examined using mathematical analyses and simulations. In this context, a new mathematical model was introduced and various number of simulations were performed in order to show whether conventional buffer management solutions are appropriate for WSNs. The results obtained from simulations were compared with each other and the proposed our new mathematical model. Through the investigations of buffer management solutions for WSNs the usage of memory and its optimality was tried to be come out.

It was found that conventional buffer management solutions are not appropriate for WSNs and they don't satisfy WSN specific needs. The utilization of buffer either would be sub-optimal or the prioritization between packets could not be supported in these buffer management approaches. There is a clear need a new approach for buffer management in WSNs. In here, we propose a novel buffer management solution that improves the general performance of Medium Access Control (MAC) layer plans, in particular those crafted for WSNs. The success of our proposed solution were discussed and it was compared with other well-known buffer management solutions. The comparison results in different plots are presented in this study.

**Keywords:** Wireless sensor networks, buffer management, MAC layer.

# KABLOSUZ ALGILAYICI AĞLARDA OEK KATMANININ PERFORMANSINI İYİLEŞTİRMEK İÇİN YENİ BİR ARABELLEK YÖNETİM ÇÖZÜMÜ

## ÖZ

Kablosuz Algılayıcı Ağ (KAA) bir ortamdaki fiziksel değişiklikleri tespit eden ve anlamlı bilgileri merkezi bir noktaya daha ileri inceleme için ileten otonom bir ağdır. KAA'lar kaynak-kısıtlı dağıtık sistemlerin önemli bir tipidir. Algılayıcı düğümler üzerinde enerji, bellek, hesaplama kapasitesi, depolama, iletişim menzili vb. birçok kısıt bulunmaktadır. Tüm bu kısıtlamalar verimliliği ve etkinliği KAA'lar için çok önemli ve oldukça gerekli nitelikler yapmaktadır.

Bu çalışmada, algılayıcı düğümler üzerinde farklı iletişim katmanlarında kullanılabilen tampon yönetim mekanizmaları matematiksel analizler ve bilgisayar benzetimleri kullanılarak incelenmiştir. Bu kapsamda, geleneksel tampon yönetim çözümlerinin KAA'lar için uygun olup olmadığını göstermek amacıyla yeni bir matematiksel model tanıtılmış ve çeşitli bilgisayar benzetimleri gerçekleştirilmiştir. Benzetimlerden elde edilen sonuçlar birbiriyle ve önerilen yeni matematiksel modelimiz ile karşılaştırılmıştır. KAA'lar için tampon yönetim çözümlerinin incelenmesi vasıtasıyla belleğin kullanımı ve bunun başarımı ortaya konmaya çalışılmıştır.

Geleneksel tampon yönetim çözümlerinin KAA'lar için uygun olmadığı ve KAA'ya özgü gereklilikleri karşılamadığı bulunmuştur. Bu tampon yönetim yaklaşımlarında tampon kullanımı ya optimum seviyenin altında kalmakta ya da paketler arası önceliklendirme sağlanamamaktadır. KAA'larda tampon yönetimi için yeni bir yaklaşımın gerekli olduğu açıktır. Burada, Ortam Erişim Kontrol (OEK) planlarının özellikle KAA'lar için olanların genel anlamda performansını iyileştiren farklı yeni bir tampon yönetim çözümü önermekteyiz. Önerilen çözümümüzün başarısı tartışılmış ve yaygın diğer tampon yönetim çözümleri ile karşılaştırılmıştır. Karşılaştırma sonuçları farklı grafikler şeklinde bu çalışmada sunulmuştur.

**Anahtar Kelimeler:** Kablosuz algılayıcı ağlar, arabellek yönetimi, OEK katmanı.

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# NOMENCLATURE

**Acronyms**

| | |
|---|---|
| WSN | Wireless Sensor Network |
| IoT | Internet of Things |
| MEMS | Micro-Electro-Mechanical Systems |
| QoS | Quality of Service |
| HWSN | Heterogeneous Wireless Sensor Network |
| MAC | Medium Access Control |
| ADC | Analog to Digital Converter |
| TDMA | Time Division Multiple Access |
| CW | Contention Window |
| ACK | Acknowledgement (packet) |
| CSMA/CA | Carrier-Sense Multiple Access with Collision Avoidance |
| SQSP | Single-Queue Single-Priority |
| MQMP | Multi-Queue Multi-Priority |
| SQMP | Single-Queue Multi-Priority |
| OBMS | Optimum Buffer Management Solution |
| FIFO | First In, First Out |
| LIFO | Last In, First Out |
| pps | Packets Per Second |
| m | Meter |
| sec | Second |
| RX | Received Packets |
| TX | Sent Packet |
| DX | Meaningful Data Packets |
| CSMA | Carrier-Sense Multiple Access |
| SMAC | Sensor MAC Protocol |
| TMAC | Timeout MAC Protocol |

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# CHAPTER 1

## INTRODUCTION

Recent years have seen the growth of the WSN as part of the IoT, which enables the development of a giant pervasive machine that can both sense and affect its environments [1]. Thanks to the rapid development of MEMS, WSNs has become in real. As an important task to sense environmental changes, WSNs have many different application areas such as environment observation, vehicle traffic monitoring, habitat monitoring, industrial automation, health applications and etc. [2]. The common feature of all these applications is that they all have some unique characteristics and each one should be treated separately and comprehensively therein. It is required that the solutions proposed for WSNs should take into account the constraints and the capabilities of sensor nodes.

### 1.1 Wireless Sensor Network and Its Limitations

The WSN can be defined as a new communication form in which many sensor nodes work together and in cooperation to extract required information from a physical area. WSN offers a different network concept that aims not only to transfer raw data between end nodes but also to produce meaningful information from collected data [3]. However, this is not a case for traditional wired or wireless networks. In these networks, the endpoints just put data on the network and it is requested from the network only transmitting this data in end-to-end fashion. The QoS requirements such as reliability, delay, fairness, throughput etc. are also taking into consideration during the transmission of packets in such networks. But in a WSN, many or all of the nodes in a network is part of the same application and their aim is same i.e. getting useful information from an interested area in an energy efficient manner. From this point, fairness in WSN is not so important as in traditional networks and the meaning of reliability changes in this new network concept. According to traditional networks the reliability is defined as just reliability of transmitting data, while in WSN there are

different reliability definitions [4,5]. Shortly, some definitions and terms that are used for traditional networks in generally could have a different content in this new networking concept.

In addition to the fact that WSN offers a different network concept, there are many issues which are overlooked most of the time in traditional networks should be handled very carefully in WSNs. Although sensor nodes have many capabilities, these capabilities can be quite limited due to cost constraints [6]. For instance, a cheap short-range radio is attached on a sensor node and packets are transmitted from source to destination through intermediate nodes with the help of this radio in a hop-by-hop manner. Thus, WSNs need a routing protocol which has very high adaptation capability due to the difficulty of hop-by-hop routing in an infrastructureless network. It is demanded that the sensor nodes should be as low-cost as possible since in an application a great number of them are used range from a hundred to several thousand [7]. The lifetime of the network is hardly dependent on the power source of sensor nodes and considering that the sensor nodes mostly use unchangeable battery as a power source, it is obvious that the energy expenditure should be kept under control in WSNs [8]. The error-prone nature of wireless links, harsh environmental conditions and frequent topology changes in WSNs make the QoS provisioning in an energy efficient way very problematic [9]. There are a lot of works and researches which propose an effective solution in connected with the limitations of WSNs. Some of the main limitations and related issues of WSNs are given in below as a list:

- The wireless medium is shared with different sensor nodes, therefore a distributed and efficient medium access plan should be employed among sensor nodes [10].

- The medium access plan should work with little power consumption because the node's energy is very limited [10].

- Besides energy, capacity of the memory, computation capability, available bandwidth and transmission range of a node are also limited [11]. Therefore, simple algorithms and protocols should be preferred for WSNs.

- Since the communication range of sensor node is shortened, there is a hop-by-hop communication between endpoint nodes. This implies that any solutions or approaches proposed for WSNs should be scalable, adaptive and energy efficient [12].

- Topology of the network continually changes with time, so the algorithms and protocols chosen for WSN should take into account these changes and its effects on QoS and energy saving strategies [13].

- Sensor nodes are deployed very densely in order to prolong the lifetime of the network. In dense networks, there is no need to work all nodes together or in other words, some nodes can be kept in sleep mode [14]. Prolonging the lifetime of sensor nodes with sleeping introduces new challenges in WSN and new approaches are needed to overcome these obstacles.

- Size of the queue in a sensor node is very limited, thereby simple, efficient and effective queue management plan is highly demanded for WSNs [15].

- Infrastructureless ad-hoc style wireless communication between sensor nodes leads to some difficulties on both end-to-end and node-to-node level communications. The problems encountered during the transmission of data such as interference, hidden terminal, exposed terminal, funnel effect etc. affects the overall performance of the network. The approaches proposed for WSNs should consider these WSN-specific problems [16].

- HWSN is a compound of simple WSNs and it consists of sensor nodes in different capabilities such as different computing power, power source and sensing range [17]. In HWSNs, an efficient service differentiation mechanism

is needed and the QoS requirements for each traffic type should be handled carefully in the proposed solutions [18].

- In order to prolong network lifetime some sensor nodes are put in sleep mode while other nodes are kept in active mode for sensing and communication. Sleeping the node helps to save more energy at nodes, but this technique has also some side effects such as sleep latency [19]. How to overcome these side effects and which mechanisms should be employed are important questions waiting to be answered.

- Delay sensitive and bandwidth hungry applications such as real-time, multimedia and mission critical applications make the latency problem much worse and need more brilliant solutions [20,21,22].

Thus, providing an all-in-one solution for WSNs is quite challenging and even impossible task not only due to the limited nature of WSN's resources but also the complex interactions between different kinds of network parameters and the 'unstandardized' intrinsic structure of the sensor nodes.

## 1.2 Study Objectives and Motivations

WSNs are spatially distributed autonomous sensor nodes that are used to monitor physical or environmental changes and aggregate relevant information about events and their locations [23]. In accordance with aggregation rules on the sensor nodes, some events in an area could be more important than others and they should be reported more effectively and rapidly. Therefore, some packets could be more important or more valuable than others, even if they all belong to the same class of traffic. For instance, in a monitoring application that checks temperature and humidity, routine and expected values are not so important and valuable as unexpected and uncommon values [24]. Although packet differentiation among different classes of traffic is generally employed to provide QoS in WSNs [25], it is an undeniable fact that packets with different priorities could be in the same traffic class. Thus, it is clear that WSNs

need packet-level prioritization, even if the packets were currently differentiated as class or flow based.

WSNs are composed of different number of sensor nodes that are cross-linked with wireless links. Simply, a sensor node is equipped with four basic units which are the units responsible for sensing, processing, data exchanging and powering [7,26]. However, there are some stringent constraints on the sensor nodes such as low memory capacity, non-complex computation, limited battery, shortened transmission range and etc. Due to the hop-by-hop wireless communication, packets can be easily lost on overly congested intermediate nodes or error-prone links. If a packet loss is experienced on a WSN, then a re-transmission or another mechanism should be performed to ensure reliable messaging [27]. However, from the application point of view, packet recovery and error correction mechanisms are wasteful in terms of energy. The lifetime of the network is hardly dependent on the power source of sensor nodes and considering the fact that most of the time sensor nodes use unchangeable battery as a power source, it is obvious that energy saving has a great importance in WSNs. Since energy is a critical resource for WSNs, many WSN researches and developments depend on it directly or indirectly [28,29]. But, battery is just one of the limited resources of sensor nodes. Computation capabilities of sensor nodes are also limited because of the intrinsic structure of the nodes. Therefore, simplicity of an algorithm or protocol proposed for WSNs determines its success. The memory provided in the sensor node is a limited area that makes effective memory management more important for WSNs. Especially in QoS provisioning, the buffer management strategies and the capacity of the buffer have significant effects on the provided service qualities [15,30,31]. In this work, we are going to investigate what are the impacts of buffer management solutions on MAC layer performance in WSNs and propose a novel buffer management solution to improve the general performance of MAC layer. The MAC layer as an important component of the communication unit on sensor nodes will be taken under examination in here because the most energy consumption on the sensor nodes is originated from this unit. The well-known buffer management solutions employed by MAC layer will be investigated whether they meet the

requirements of WSNs and they will be compared with our proposed new buffer management solution through different methods. Mathematical modelling and simulations will be helped us during the examination and the confirmation of our proposed solution performance. The performance of different buffer management solutions will be evaluated in terms of their throughput, buffer utilization and prioritization capabilities.

## 1.3 Thesis Outline

The remainder of this thesis is organized as follows: Following the Introduction, Chapter 2 presents a literature review of a number of approaches related to medium access control and buffer management solutions in wireless sensor networks. The chapter is divided into three subsections: MAC Solutions for WSNs, Buffer Management Solutions for MAC Layer in WSNs, and Discussion. The chapter aims to provide a background to the research by summarizing the features and shortcomings of currently well-known solutions proposed for WSNs and show the uniqueness of this study by documenting the problematic sides of present solutions observed during extensive surveys and investigations in the research field.

Chapter 3 introduces a new mathematical model to compare different buffer management solutions proposed for WSNs and gives the assumptions that are needed during the construction of the model. The model is applied on different buffer management solutions and the expected cost of each solution is uncovered through mathematical analysis. In addition to proposed mathematical model, which is used for analysis and comparisons of the general performance of buffer management solutions, a clear and simple explanation of the problem which is attempted to be solved within this thesis is also given at the end of this chapter.

Chapter 4 presents the details of performed simulations and important simulation parameters that affect the simulation results directly. Simulation results assessing the performance of the proposed buffer management solution could be also found in this chapter. The chapter concludes with a discussion presenting possible critiques of the

well-known buffer management approaches in context with their appropriateness to WSN environment.

Chapter 5 outlines the findings of this study and discussing the main contributions of the thesis to the research field. This final chapter also identifies the limitations of this work and depict possible future research directions to explore and improve the capabilities of present WSN technologies.

# CHAPTER 2

## BACKGROUND AND LITERATURE REVIEW

This chapter provides a survey of the well-known approaches in MAC protocols specifically designed for WSNs and the buffer management solutions widely employed by many sensor nodes at MAC layer. Since buffer management solutions are strictly depended on QoS provisioning approaches, a review of existing researches on QoS provisioning in WSNs is also mentioned in here. The chapter is divided into three subsections. The first section contains information about MAC solutions for WSNs and their unique features proposed to remediate the limitations of WSNs. The second one is about buffer management solutions and the known challenges caused by the limitations of memory in sensor nodes, and also includes information on approaches for QoS provisioning in WSNs. Following the literature review in first two sections, the third section presents a discussion focusing on the lack of works jointly addressing packet level prioritization and buffer management in WSNs. Before proceeding to the first section, a general background is provided in below to give a basis for more specific issues that follow.

The developments in low power wireless communications and MEMS technology have created a new technological direction called WSNs. A WSN is composed of different number of sensor nodes and all of them are to work together and in cooperation to accomplish a given task. The sensor nodes should be always in touch and able to communicate with each other to ensure that there is no isolated parts in the network. The communication between sensor nodes is provided over wireless links. Simply, a sensor node is equipped with four basic units which are sensing unit, processing unit, transceiver unit and power unit [7,32]. It may also have application dependent additional components such as a location finding system, a power generator and a mobilizer. Sensing units can be divided into two subunits: sensors and analog to digital converters (ADC). Sensors are aware of any changes in surroundings and if they are triggered by anything then an analog signal is produced and sent to ADC for

analog to digital conversion. After the digitalization the signal can be processed by processing unit. The processing operation needs memory, thereby a small memory is attached to the processor. Instead of sending the raw data, partially processed data is sent via transceiver unit to a central node which is usually called as sink. The transceiver unit is used for connecting the node to the adjacent nodes and the rest of the network. The most critical unit in the sensor node is power unit and prolonging the lifetime of WSNs by reducing the energy consumption of sensor nodes is still one of the most important open research areas for WSNs. Apart from the energy saving strategies, a power generator system like solar cells may be combined with power unit for harvesting energy but this alternative solution causes an increase in cost of sensor nodes. Since the communication subsystem of sensor nodes is the greediest source of energy dissipation, transceiver unit has received substantially more attention among researchers in WSN community. The common structure of a sensor node and a simple WSN is shown in Fig. 2.1.

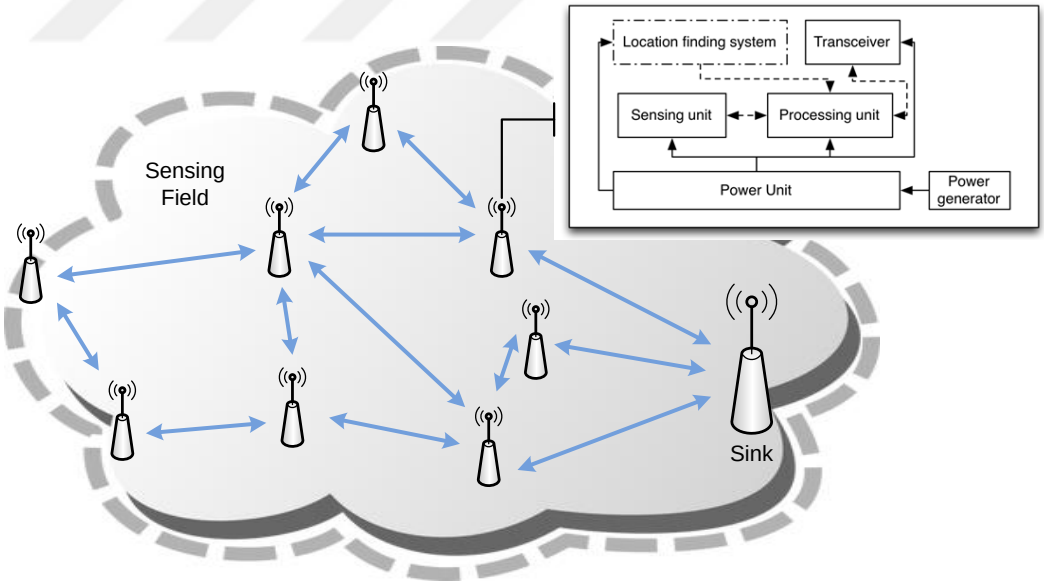


**Figure 2.1** The structure of a sensor node and a simple WSN

There are many studies that focus on optimizing energy consumption and provide quality of service (QoS) in WSNs. Designing an efficient Medium Access Control

(MAC) protocol is of paramount importance for WSNs because the MAC layer coordinates nodes' access to the shared wireless medium and it defines the basis of node-to-node communication. Experimental results confirm that the communication subsystem of sensor nodes is the greediest source of energy dissipation [33]. As an important component in the communication subsystem of sensor nodes, MAC layer and the solutions leaded by this layer have attract more attention in comparison with other layers. In the early years of WSN researches, developers were mostly concerned with energy saving strategies because sensor nodes were usually limited in terms of power supply, and the most important concern among researchers was how this limited energy could be used efficiently. However, in recent times, some new technologies have been introduced for WSNs such as low-cost visual sensor devices and microphones that all has fostered the QoS-aware protocols [34]. Therefore, throughput and latency is being a big concern in the research community of WSN nowadays.

## 2.1 MAC Solutions for WSNs

The MAC layer is primarily responsible for regulating access to the common medium and ensuring that there are no point-to-point communication errors. This section reviews the cornerstone MAC layer solutions proposed for WSNs in general, discusses the unique characteristics of such protocols, and tries to give a classification of present MAC protocols. Although different classifications can be made for MAC layer solutions in WSNs according to their different specifications, there are two main approaches for regulating access to shared wireless medium: contention-based and reservation-based approaches. Thus, a MAC protocol is based on one of those two approaches or a combination of them [35]. In the following, we are going to discuss the key features of these approaches and give a representative MAC solution for each approach to clarify them more deeply.

The first protocol introduced in here is SMAC, which is a contention-based MAC protocol for WSNs proposed in 2002 by Ye et al. [36]. The main purpose of this protocol is to reduce energy consumption by putting sensor nodes in sleep mode periodically and thereby extends the lifetime of nodes and the network. Although such

sleep schedules save energy, they bring significant packet latency as well. In SMAC, neighboring nodes form virtual clusters so as to set up a common sleep schedule and to become much more scalable. However, in case a node is located in different clusters, that node has to wake up at the listen periods all of these different clusters. One of the deficiency of SMAC protocol is this possibility of following different schedules that causes more energy consumption because of idle listening and overhearing. Shortly, SMAC introduces a scalable and an energy efficient MAC protocol, but its periodic sleeping approach causes some extra delay in the transmission of packets. Moreover, there is no packet differentiation mechanism in SMAC protocol that leads to blindness in traffic prioritization.

The choice of Wu et al. is Time Division Multiple Access (TDMA) a contention-free scheme used for accessing the shared medium in WSNs. TDMA is one of important implementation of reservation-based MAC protocols. TDMA based shared medium access is scheduled by each cluster independent of other clusters and sensor nodes can save a significant amount of energy by turning-off radios during unallocated slots. However, there is still an important problem that remains unsolved for WSNs which is called inter-cluster collision problem. This problem can easily occur when a time slot is used by two neighboring clusters. Self-Reorganizing Slot Allocation (SRSA) mechanism which is proposed by Wu et al. try to solve inter-cluster collision problem with carrier sensing [37]. However, the approach carrier-sensing used for inter-cluster communication causes an increase on the overhead. In addition to large overhead, the slot-overlapping problem can be experienced easily among different clusters because slots are assigned independently. Therefore, slot reorganization and mobility management is a big problem for SRSA. Moreover, time slots are reserved to nodes even if they have no data to transmit, that result in inefficient spectrum usage and increase packet latency. As in SMAC, there is no discussion about packet differentiation or traffic prioritization in this MAC layer solution which is TDMA based and empowered with SRSA.

In the literature, a wide range of hybrid techniques were offered to minimize the known side-effects of current MAC protocols by combining them into one single protocol. The idea behind ZMAC proposed by Rhee et al. is this thought. Contention-based and reservation-based approaches are used together for improving the channel utilization in ZMAC protocol [38]. In a WSN deployment, ZMAC uses a plan for time slot assignment that each node within the two-hop communication neighborhood are assigned to different slots. The CSMA together with TDMA, a node is able to contend for transmission in any slot if that slot is not used by the owner. Consequently, Z-MAC switches to CSMA under low contention for saving more energy; but under high contention it switches back to TDMA for better channel utilization. However, there are some challenges facing hybrid implementations especially in dense network conditions. In ZMAC, the sender is forced to wait for a predetermined of time to ensure that the slot is not used by the owner. Each receiver also is forced to stay awake during transmission in order to control whether it is the intended receiver. Therefore, the slot capturing mechanism brings about an extra energy consumption on the sensor nodes. In addition, there is no mechanism for packet differentiation in ZMAC and it causes performance degradation in high contention and dense network condition in this protocol.

In the early stages of WSN researches, efficient data delivery was not the first concern of the researchers and they mostly traded throughput and delay for energy efficiency. However, to support multi-task and meet delivery requirements of bursty traffic, new protocols are being developed [39]. In the following, the important QoS-aware MAC protocols are introduced which are jointly addressing energy efficiency and data delivery performance.

An important QoS aware MAC protocol for WSNs were offered by Saxena et al. and they advocate the contention-based approaches for WSNs [40]. This MAC protocol is distinguished from others with its own traffic prioritization mechanism. Supporting QoS for multimedia transmission in WSNs and conserving energy without violating the QoS requirements are the main intentions driven by this protocol. It is assumed

that there are three types of traffic carried in the network by this protocol: streaming video, non-real-time and best effort. Some important statistics are collected from the network and the protocol adapt itself to the current conditions of the network by updating Contention Window (CW) size and duty cycle in accordance with the collected information. The power saving is accomplished by using adaptive duty cycles according to the type of current traffic in the sensor node. Therefore, sensor nodes have their own sleep-listen schedules. The CW resizing is used for service differentiation i.e. higher priority traffic has smaller CW size. As a result of this smaller CW size, packet delay could be reduced for high priority traffic. The highly adaptive nature of the protocol imposes some difficulties on network operations such as overhead and complexity. Moreover, idle listening or early sleeping can occur in the network due to the unsynchronized sensor nodes and the packets which belong to a lower-priority traffic may experience abnormally high latencies in this protocol.

Deterministic bounds for node-to-node reliability and delay is studied by Suriyachai et al. and they propose the QoS-MAC protocol to ensure such QoS guarantees for local transmission [41]. Their main focus is developing a suitable shared medium use strategy for applications requiring a predefined level of reliability and delay assurance. A collision-free TDMA scheme is preferred for this task because it is believed that TDMA based medium access is more suitable for delay-guaranteed applications. The time line is divided into fixed-size units (called as epoch) and in each unit, a sensor node has several slots for only single message exchange. A message exchange occurs only if a packet is delivered to next hop successfully and an ACK is received within an epoch. Thus, node-to-node latency for all nodes is smaller or equal to epoch size in the worst-case. Control message is used at first slot for indicating that the sensor node has no data and freeing up consecutive slots. Each node in the network has different duty cycles in order to reduce energy consumption according to the number of child nodes. The time is synchronized with parent nodes periodically thereby any synchronization error propagates to the other nodes increasingly. Moreover, nodes are supposed to be aware of its position in the parent-child hierarchy for slot allocation, scheduling and duty cycling. Because of this, the proposed MAC protocol is not

scalable for large networks. Additionally, delay and reliability assurance may not be possible to obtain with requested throughput for different traffic types.

A well-studied MAC protocol for WSNs is developed by Yigitel et al. [42]. The protocol which is called Diff-MAC by the developers is introduced as a QoS-aware protocol with service differentiation and hybrid prioritization. Their preference for accessing the shared-medium is contention-based CSMA/CA. Inefficient use of channel is strongly addressed by Diff-MAC and this issue is tried to be resolved with employing an effective service differentiation mechanism. The main application area of Diff-MAC is delivering multimedia content over infrastructureless wireless multimedia sensor networks. There are some important differences that distinguish Diff-MAC from previous ones in providing QoS that deserve to be mentioned in here separately:

(a) Long frames are fragmented and transmits as a burst in order to reduce retransmission cost.

(b) Size of the contention window (CW) is changed according to traffic specifications on sensor nodes in order to reduce collision probability and node-to-node packet delay.

(c) Adaptive duty cycling is employed to manage energy usage and packet latency requirements.

(d) Multi-tiered prioritization is used for providing fairness to all traffic classes and all sensor nodes in WSN.

The quick adaptive nature of Diff-MAC for the changing network conditions bring a big advantage to Diff-MAC compared to other MAC protocols. On the other hand, continually monitoring network activities and collecting relevant statistics increase the complexity and the implementation cost of Diff-MAC as well. Furthermore, lack of time synchronization between neighboring nodes can cause early sleeping problem that result in additional packet latencies in the network.

The cross-layer design is one of the most promising approach, especially for providing both energy efficiency and QoS support in WSNs [43]. Cross-layer optimization is an escape from the concept that put strict boundaries between network layers that causes ineffective use of information that belongs to different layers. In cross-layer design, a number of parameters are jointly controlled and a specific layer becomes available across layers as certain functions might benefit from that layer's information.

Heimfarth et al. propose an asynchronous cross-layer medium access control protocol named GB-MAC [44]. GB-MAC introduces a cross-layer design which combines the network and MAC layer. The primary aim of GB-MAC is to put forward a solution regarding the latency problem caused by node sleeping. The latency is reduced with the help of a special group of nodes which works as a highway for delay-constrained traffic. These nodes are called “backbone” in their works. The backbone is constructed by the network protocol based on MAC layer modifications. This means that network layer feeds MAC layer with necessary information for tuning. Operational parameters are exchanged between network and MAC layer, and the number of active nodes in the network can be reduced without affecting the routing performance. Unnecessary nodes are turned off by MAC layer according to the involvement of backbone construction to reduce energy consumption.

Another cross-layer design is proposed by Xiong et al. [45] and they advocate the combination of MAC and application layer. Unlike GB-MAC, in this protocol authors try to develop an application-specified protocol. By integrating application semantics with known a MAC protocol proposed for WSNs, the unrequested redundancy among reported data could be reduced with the help of negotiation between reporting nodes before transmission. The authors claim that they found a more energy efficient version of the well-known MAC protocols by implementing the approach they developed. In this approach nodes organizes themselves into clusters and cluster-head is responsible for collecting data from all the cluster members and reduced it through removing duplicate sequences.

A panoramic vision of the approaches proposed for MAC layer in WSNs clearly shows that the evolution of such approaches is mainly from energy efficient protocols to QoS aware ones. While many different approaches have been proposed to provide demanded QoS in WSNs, sometimes different combinations of the known approaches outperform conventional solutions and they become important alternative solutions for WSNs. It is possible that there are different evolution scenarios [39], apart from the ones mentioned in here, but it is undoubtedly true that the QoS is an indispensable requirement for WSNs in the light of recent developments. On the other hand, the management of buffer is highly critical for QoS provisioning and it has an important impact on QoS support since the birth of computing networks [46]. Therefore, a review of buffer management solutions implemented by different MAC layers is presented and discussed in the following section.

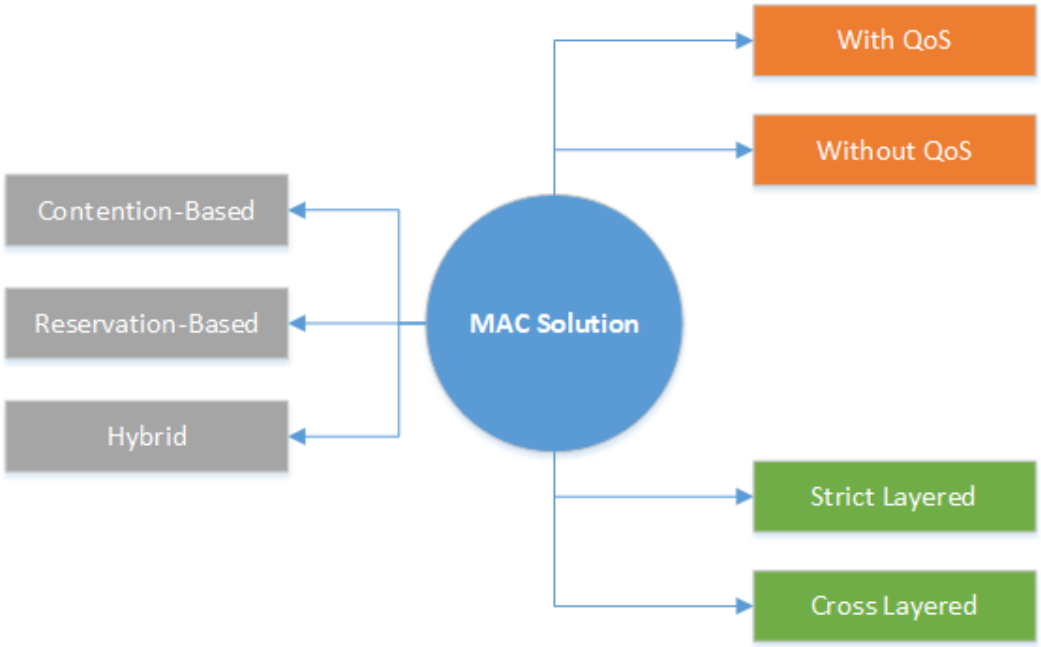


**Figure 2.2** A Classsification of MAC layer solutions

## 2.2 Buffer Management Solutions for MAC Layer in WSNs

In early times of WSN researches, it has commonly been assumed that QoS is not so important as energy efficiency for WSNs. However, development of new technologies is pushing WSN into different application areas over time. With the emergence of new technologies associated with sensor nodes and their components, the traffic classes with different types and different priorities make QoS a main and necessary part of WSN researches. In order to meet the strict requirements of different applications and the traffic characteristics of WSNs, a great number of new approaches have been developed and proposed in the literature. QoS is tried to be provided with various methods and approaches on different layers of communication protocol stack in such approaches [47].

MAC layer is one of the most noticeable layer according to many WSN researchers to optimize important parameters that affect overall network performance. It is because of the fact that the point-to-point communication and the related coordination are under the responsibility of this layer and the most of the energy is consumed by MAC layer [25]. Chronologically, energy-efficient approaches were at the center of this layer in early years, but lately, both energy-efficient and QoS-aware approaches have become one of the main research area in MAC layer solutions proposed for WSNs [39]. The researches on QoS support in WSNs primarily concern about the MAC layer and its performance. The compliance of MAC layer with other layers is also important for QoS insurance because the MAC layer rules all other upper layers [48]. This means that MAC layer affects all upper layers in terms of determining the boundaries of QoS which is provided by the upper layers in communication stack.

As in Khan’s [49] paper, one of the attempts for achieving QoS at MAC layer is using buffer management and scheduling strategies. There are many different approaches about buffer management in the literature, but they are all basically based on two different strategies indeed. In early times of WSN researches when packet differentiation was not required and there was just one type of packet in the network, Single Queue and Single Priority (SQSP) based approaches were preferred by the

WSN researchers. Generally, in these approaches, packets are buffered in FIFO (First In First Out) manner and it is assumed that all packets have the same priority. The most important criterion that is tried to be provided in these approaches is energy efficiency [50,51,52]. However, single priority based approaches ignore prioritization requirements among different types of packets.

It is clear that different applications require different QoS assurances. The different specifications of transported data, main limitations of sensor nodes and hop-by-hop wireless communication characteristics make QoS provisioning more problematic for WSNs. Though different layers of communication could be used individually or together to provide QoS requirements of the application, MAC layer based approaches attract much more attention in comparison with other layers [53]. In order to provide packet differentiation and prioritization among different traffic classes in WSNs, Multi-Queue Multi-Priority (MQMP) approaches come into existence. In these approaches, packets are differentiated with their types and priorities, then packets are buffered in different queues in FIFO manner and served according to their priorities. With the help of multiple queues, packets having different priorities can be differentiated and the QoS requirements of application are tried to be satisfied with priority based scheduling algorithms [25]. Multi queue based buffer management solutions share available buffer space among different queues. One of the main drawback of these multi-queue approaches is that they reduce the utilization level of buffer in general.

One of the well-known works which adopt MQMP belongs to Liu et al. [54]. This paper proposes Q-MAC protocol which uses FIFO queue structure, differentiates coming packets according to their priorities into five queues and services them by ensuring higher priority packet is always the first manner. It is stated that the Q-MAC provides more efficient packet differentiation and prioritization than single-queued S-MAC protocol at the expense of almost same amount of energy. In PQMAC proposed by Kim et al. [55], multi-queue and FIFO approaches are adopted for QoS provisioning and low-priority packets are kept waiting until the packets in the high priority queue

are exhausted. But, in this scheme, there are just two queues: one of them for high priority packets and the other for low priority packets. Similarly, Saxena et al. [40] propose to divide the buffer space into two queues and classify traffic as multimedia and non-multimedia. Packets are buffered in these two queues in FIFO order and multimedia packets are served firstly. Multi-queue is preferred for this approach, which attempts to meet the QoS requirements of multimedia contents with a relatively small extra energy consumption. There is also different queueing strategies as in [56] in which packets are buffered in two different queues on the sensor nodes after checking whether they are part of a real time traffic. One interesting paper about sharing available buffer space with different queues was written by Shwe et al. [57]. In this paper, researchers propose a multi-layer WSN and each layer is associated with a priority queue in the network. But, if there is an available space on the buffer, arriving packets are accepted without paying attention if packets belong to the same layer or different ones. Thus, unnecessary packet losses are being avoided. Multi-queuing and FIFO structure are also adopted again in this work.

Apart from the FIFO structure, Xiong et al. [58] recommend the LIFO (Last In First Out) approach for real time communication in WSNs. Since real time contents require a more effective transmission due to time constraints, LIFO outperforms FIFO structure especially in congested network conditions. In that paper, as in the others, multi-queue approach is used for differentiating traffic classes. Another interesting buffer management mechanism is the one that offers a metric which is used for packet forwarding. This metric is called by inventors Söderman et al. [59] as Smart-Gap. Smart-Gap uses the gap metric to prioritize packets. As a queuing policy, Smart-Gap discards the packet with the lowest gap metric. In other words, packets in bursts have higher probability of being discarded than single packets. When used as a forwarding strategy, Smart-Gap forwards the packet with the largest gap metric. This means that sparsely distributed packets are more likely to be forwarded than clustered ones. As a result, trends in the monitoring data are much more clearly visible at the end point.

The last two of the aforementioned studies above, particularly focused on the performance in congested network conditions for WSNs. However, this is overlooked in most studies [58] and many of the researches just focus on congestion avoidance or recovery methods. Congestion avoidance and congestion recovery methods either try to avoid or recover from the congestion, hence they can do nothing to the performance degradation but wait for recovery when congestion does take place. Actually, performance degradation during congestion cannot be dismissed in WSN applications [58]. Congestion is inevitable in WSNs, due to the unstable environment of wireless communication and the traffic dynamics such as traffic bursts and many-to-one multi-hop traffic loads [60]. The last two researches are concerned with the time-constrained data set and delay-tolerable data set respectively. This emphasizes the fact that congestion in both data sets is possible for WSNs and QoS should be provided even under these circumstances.

## 2.3 Discussion

This thesis is based on and supports the idea that the buffer management mechanisms should be rethought from the perspective of current and possible future WSN requirements, far from the paradigm driven by conventional network concept. Approaches proposed for WSNs should take into account the limitations of WSNs and unstable and infrastructureless communication of wireless environment. However, known buffer management solutions either waste the available limited buffer capacity in order to support QoS or overlook the prioritization issues among different types of packets carried on the network. Limited buffer capacity of the sensor nodes should be used efficiently and effectively. For instance, let’s suppose a network that supports two different traffic classes and most of the packets flowing through that network belong to a single traffic class. In this case, if congestion occurs, the buffer utilization of a sensor node is approximately two times better for single-queued buffer management mechanisms than double-queued buffer management mechanisms. Hence, multi-queue approaches will reduce the buffer utilization in such networks where a single traffic class dominates the network. However, if a higher priority packet

is generated and sent under congested network conditions, the probability of losing this higher priority packet is raised by single-queued buffer management mechanism. Since there is no packet differentiation and prioritization in this mechanism, the new packets are dropped because of lack of empty space on the buffer even if they have higher priority. Considering both high and low priority packets generated in different parts of a single large network, it is clear that in any case, buffer management mechanisms employed on sensor nodes result in inefficient or ineffective use of available buffer space. This is because either buffer utilization will be sub-optimal or the prioritization between packets could not be supported. It is required a new buffer management approach in which there is no need for static or predefined priority mechanisms. This approach should provide also high buffer utilization and packet differentiation at the same time without sacrificing one to the other.

The memory, we are calling sometimes it as buffer in here, is one of critical resources in regards of packet transmission effectiveness [15]. Capacity of the buffer and the mechanism used for buffering, differentiating, prioritizing and forwarding is important for transmitting packets to target node in an efficient way. Mechanisms used on the buffer are decisive because they actively affect the amount of aggregated packets on the sink node. At this point, there are main two approaches in the literature for buffering [61]. Both of these two approaches are known and generally used in traditional wired and wireless networks. The first approach is called in this thesis as SQSP (Single Queue Single Priority) which is FIFO (First In First Out) structured and single queued buffer. In this buffer management mechanism, priorities of the packets are ignored and treated as if they all were in the same priority. Simplicity is the most powerful side of this approach. The second approach is called as MQMP (Multi Queue Multi Priority) which is also belongs to FIFO scheme but two or more buffers can be used for buffering and in accordance with an inner plan, packets are differentiated and prioritized through considering the their priorities. Furthermore, buffers are strictly separated with each other and each queue is used for packets having different priorities. However, higher priority buffers in sensor nodes are empty most of the time but they fill up quickly when an event occurs. Although some lower priority buffers are empty,

these empty buffers are not used for high priority packets because of the separated buffer management plan in this buffer management approach. At this point, most recently received high priority packets are dropped because there is not enough space in high priority queues. Apart from aforementioned drawbacks of conventional buffer management solutions, the FIFO (First In First Out) scheme widely used in such solutions has also lead some problems [62] in WSNs. For instance, a packet with delay constraint and higher priority can be inserted at the behind of the buffer as a last packet. But in this case, there is no mechanism that assess whether it is delivered successfully in its time limits. Furthermore, if the packets are not inserted as last item or inserted according to their minimum or maximum waiting time, the delay constraints of the packets could be met more easily. However, most of time that opportunity is ignored or left unattended in such conventional buffer management solutions.

In SQSP approaches, the utilization of buffer is comparably greater than MQMP, but there is no differentiation between different priorities. While in MQMP approaches, differentiation and prioritization of different traffic classes in the network can be supported at the expense of reducing utilization level of the buffer in general. Another important issue in MQMP approaches is the need to use a predefined classification and prioritization mechanism. For instance, considering a network that wishes to use the MQMP approach on the sensor nodes, it must be clarified that how many different traffic classes should be supported in that network in the first place. It is difficult or impossible to change the number of priorities defined on the network after deployment of the sensor nodes. Clearly, this is undesirable for WSNs which can be highly flexible, dynamic and heterogeneous. Traffic priorities in WSNs are not static, number of priorities can change dynamically in time depending on the network conditions.

Apart from the prioritization issues, sleeping the node which is the most important and widely used mechanism for energy saving on different MAC layer plans in WSNs [63], has a direct impact on packet transmission rate. Especially in congested network conditions, sleepy nodes cause more packet losses. SQSP and MQMP based approaches are mainly used in traditional networks, but they are actually not

appropriate for WSN environments since they disregard buffer capacity and energy limitations or duty-cycle and FIFO based problems. These issues are important for WSNs and to be handled much more carefully [22].

Based on the concerns elaborated above, the author of this thesis deals with the issues of buffer management in WSNs regarding node-based and network-based limitations. In this context, a mathematical model is proposed to compare different buffer management solutions in terms of their efficiency and their effectiveness. Besides mathematical model, a new buffer management solution is introduced in here as well. In our solution we hybridize well-known buffer management solutions and try to improve and adapt their features for WSN environment. Packet differentiation and packet prioritizing properties are taken from MQMP based approaches but these features are served on a single queue as in SQSP. So, we supply an extra space for incoming packets and provide prioritization between packets in different flows at the same time. Our solution proposes a simple, effective and also efficient buffer management solutions for WSNs. Before presenting the mathematical model and the analysis, the next chapter explicitly sets out the boundaries of the proposed model and its confirmation steps.

Last but not least, there is one more thing need to be mentioned in here to prevent misinterpretations which may be caused by a confusion between basic buffer management solutions and their different implementations. The purpose of our study is not to present a new approach for congestion control, but it is true that one of the contributions of our approach is the alleviation of congestion in the network. In fact, the motivation behind our study is revealing the shortcomings of well-known buffer management solutions that are widely used in traditional networks. These solutions are also employed by many WSNs for the time being. This is because of the fact that there isn’t a specific work which analyzes and compares basic buffer management solutions taking into account WSN based necessities. In here, it is tried to be shown that the use of traditional buffer management solutions in WSNs is inappropriate and causes many problems.

# CHAPTER 3

## ASSUMPTIONS AND MATHEMATICAL MODEL

In this chapter, the scope of this thesis is determined and a basic framework is tried to be given for the study. The details of our mathematical model proposed for comparing buffer management solutions is presented in here. After presentation of our conceptual model, a precise formulation of the problem what is being attempted to be solved in this work is also given at the end of this chapter.

### 3.1 Assumptions and Notations

In this thesis, it is assumed that a WSN is comprised of multiple sensor nodes with a small memory. Even though the memory sizes may vary in the market, the distinguishing feature of these memories is that they have quite small capacities due to the cost factor. Therefore, the first constraint which is taking into account in our conceptual model is this limitation on memory sizes.

In order to fulfill the assigned tasks, the sensor nodes first try to detect an event that occurs in the sense field and then report eventually the gathered information about the event to a central node. During this reporting process, the packets generated by the source nodes are passed through the intermediate nodes to reach the main target node, called as usually sink node. At this point, it can be easily noticed that the MAC layer, in which data exchange between sensor nodes is coordinated and managed, is one step ahead of other communication layers. Since the packets pass through the entire network in a hop-by-hop manner and the most of energy in WSN is consumed during this process, it is very clear that the MAC layer has a key role for energy efficiency. Considering that the most critical resource in the sensor nodes is energy, it is necessary for WSNs to prevent unnecessary packet losses as well as to ensure that important packets are transmitted to sink node effectively and in an energy efficient manner. Therefore, the second constraint which is taking into account in our conceptual model

is this efficiency and effectiveness problem that arises during the use of buffer on sensor nodes.

Buffer management solutions are mainly responsible for scheduling both incoming and outgoing packets on the sensor nodes. Besides, the total memory space on the sensor nodes is too low which causes buffers on the communication stack very limited in terms of capacity. For this reason, it is necessary to optimize the utilization of buffer in WSNs and it should be recognized that this necessity could not be met without a new buffer management solution that focuses on not only the limitations of sensor nodes but also the new opportunities offered by WSNs. In order to meet the desired QoS in the network, there are different approaches proposed for buffer management on MAC layer and some of them have been more popular in WSN community over time. This implicitly means that a MAC plan work with a buffer management solution compatibly while cannot work with another one. In essence, the intrinsic structure of MAC layer and the solutions employed by MAC layer are decisive on the general performance of point-to-point communication. Since end-to-end communication strictly depends on the point-to-point communication, the MAC layer also affects the communication performance between endpoint sensor nodes in WSNs.

It is very useful to analyze and test whether a new approach proposed for buffer management will provide the expected benefit in the application area before proceeding to implementation phase in order to save time and effort. Thus, buffer management solutions are surveyed and a conceptual model is developed herein for the purpose of comparing different buffer management solutions. In order to reveal what impacts of buffer management solutions on MAC layer performance in WSNs this model will be helped us during the study. The success of a buffer management solution can be analyzed and compared through this model easily. It is obvious that some basic assumptions is needed for this model. In order to make our conceptual model more clear, the following assumptions have been used while constructing the model. Furthermore, we need some definitions and notations during analysis. They are all given below:

- A buffer is a set of pockets. Pockets are empty spaces on the buffer and they are used for accommodating packets.
- Pocket at *i* index on the buffer is denoted by $C_i$. It is assumed that $C_1$ represents the first pocket on the buffer.
- Inter-service time between buffered packets is constant and denoted with α. The exact service time of packet indexed at *i* pocket on the buffer can be calculated as:

$$T(C_i) = T(C_1) + \alpha * i \tag{3.1}$$

- A packet located on the buffer is denoted with *P*. A packet can be identified with its priority and timeout information. The priority is denoted by $P_p$ and the timeout is denoted by $P_t$. It is assumed that higher priority packets have higher cost values. This means that if a high priority packet is lost or dropped during the transmission its cost will be high in comparison with a lower priority packet.
- The size of the buffer is equal to *n*. It is assumed that multi-queue approaches share this buffer space with different priority queues equally.
- The cost of a buffer management mechanism is determined with packets being lost or dropped. Packets are dropped since there is no free space on the buffer or packets are lost since packets' timeout limitations are not satisfied by the buffer management mechanism. Therefore, the cost of a pocket at *i* index on the buffer could be given as:

$$F_i = \begin{cases} 0\,, & if\ P_t \geq T(C_i) \\ P', & if\ P_t < T(C_i)\ or\ Buffer\ is\ full \end{cases} \tag{3.2}$$

*P'* represents the cost of lost and dropped packets.

- It is assumed that buffer management mechanisms try to minimize the total cost. The cost of a lost packet located at *i* index on the buffer is denoted by $F_i^L$ and the cost of a dropped packet located at *i* index on the buffer is denoted by $F_i^D$.

$$F = min \sum_{i=1}^{n} F_i = \min \sum_{i=1}^{n} (F_i^L + F_i^D) \qquad \textbf{(3.3)}$$

- It is assumed that there is an Optimum Buffer Management Solution (OBMS) that always accommodates incoming packets at right position on the buffer and delivers them within their timeout limitations. Therefore, the OBMS never experiences a packet loss or a packet drop theoretically. The OBMS is going to be used as a reference model during our analysis and the comparison between performances of different buffer management solutions is going to be made through this model.

According to our conceptual model, a simple representation of our assumptions is given in Fig. 3.1. This figure attempts to provide a base to readers on what a buffer looks like in general.

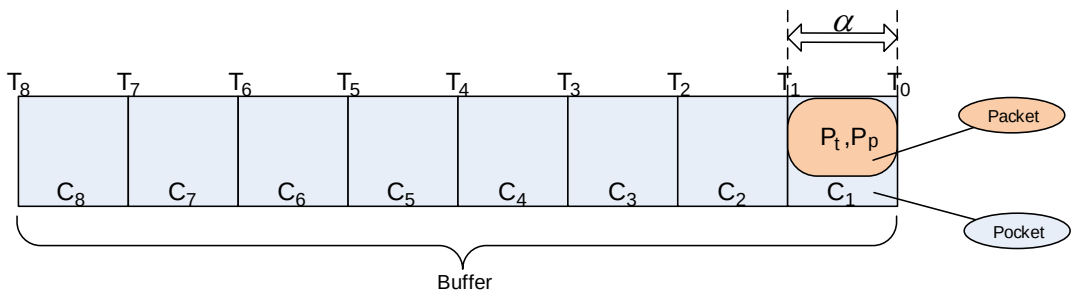


**Figure 3.1** The conceptual model of a buffer in a sensor node

## 3.2 The Mathematical Model and Analysis

We are going to investigate three buffer management solutions: SQSP, MQMP and Single Queue Multi Priority (SQMP). The SQMP is our proposed solution for buffer

management in WSNs. The analysis is based on a network in which there are only two different types of packets corresponding to low and high priority ones. In the following, we will start with SQSP and continue with MQMP and SQMP analysis respectively. SQSP and MQMP are the well-known buffer management solutions utilized on different layers of the communication stack in WSNs as well as conventional wired and wireless networks in order to meet application-based and network-based requirements. SQMP is our buffer management solution which is developed specifically for WSNs within the context of this study. As can be clearly seen throughout this thesis, the proposed solution SQMP shows a better convergence to WSN-specific limitations and QoS expectations.

### 3.2.1 SQSP

In SQSP, packets are accommodated in the buffer in FIFO manner and there is no packet differentiation or prioritization between packets. The pseudocode of SQSP could be seen in Fig. 3.2.

```
procedure SQSP
    if pkt is received or generated then
        if Q.size ≤ Max then
            Q.enqueu(pkt);
            return true;
        else
            pkt = null;
            return false;
        end if
    end if
    if medium is ready for sending packet then
        if Q.size ≥ Min then
            pkt = Q.dequeu();
            return true;
        else
            return false;
        end if
    end if
end procedure
```

**Figure 3.2** SQSP buffer management algorithm

For simplicity, the size of the SQSP buffer is assumed to be just 2 pockets. It is clearly seen that this buffer could hold at most 2 packets at any one time. It is assumed that the duration between two consecutive services on MAC layer is constant (α) and equal to each other. In other words, if first packet on the buffer is delivered at time α, the second packet will be delivered exactly at time 2α. Supposing that there are 2 packets labeled with X, Y and they are accommodated at $C_1$ and $C_2$ pockets respectively according to the OBMS. The packet in $C_1$ is going to be sent until $T_1 = \alpha$ and $C_2$ is going to be sent until $T_2 = 2\alpha$. According to the definition of OBMS, X and Y are accommodated at exactly the right positions on the buffer and they will be delivered within their timeout limits. However, SQSP could accommodate these 2 packets in reverse order. If it was so, the packet X would be lost because the timeout of the packet X is less than α. So, we have 0.5 expected packet loss for 2 sized SQSP buffer. We can expand our analysis to buffer with size of *n*:

- A packet $P_{t=\alpha}$ which is accommodated in $C_1$ by OBMS could be in $C_2$, $C_3$, ..., $C_n$ pockets in SQSP. If it was so, this packet would be lost. Thus, the expected packet loss for $P_{t=\alpha}$ can be calculated as:

$$\frac{(n-1)*(n-1)!}{\mathrm{n}!} = \frac{n-1}{\mathrm{n}} \qquad \textbf{(3.4)}$$

- A packet $P_{t=2\alpha}$ which is accommodated in $C_2$ by OBMS could be in $C_3$, $C_4$, ..., $C_n$ pockets in SQSP. If it was so, this packet would be lost. Thus, the expected packet loss for $P_{t=2\alpha}$ can be calculated as:

$$\frac{(n-1)*(n-2)*(n-2)!}{\mathrm{n}!} = \frac{\mathrm{n}-2}{\mathrm{n}} \qquad \textbf{(3.5)}$$

- A packet $P_{t=3\alpha}$ which is accommodated in $C_3$ by OBMS could be in $C_4$, $C_5$, ..., $C_n$ pockets in SQSP. If it was so, this packet would be lost. Thus, the expected packet loss for $P_{t=3\alpha}$ can be calculated as:

$$\frac{(n-1)*(n-2)*(n-3)*(n-3)!}{\mathrm{n}!} = \frac{n-3}{\mathrm{n}} \qquad \textbf{(3.6)}$$

- If the same procedure is applied to all pockets on the buffer, the cost of SQSP in average is equal to:

$$
\begin{aligned}
P_{t=\alpha} &= \frac{(n-1)*(n-1)!}{n!} = \frac{(n-1)}{n} \\
P_{t=2\alpha} &= \frac{(n-1)*(n-2)*(n-2)!}{n!} = \frac{(n-2)}{n} \\
P_{t=3\alpha} &= \frac{(n-1)*(n-2)*(n-3)*(n-3)!}{n!} = \frac{(n-3)}{n} \\
. & \quad \dots \\
. & \quad \dots \\
. & \quad \dots \\
P_{t=(n-2)\alpha} &= \frac{(n-1)*(n-2)*\dots*(2)*(2)!}{n!} = \frac{2}{n} \\
P_{t=(n-1)\alpha} &= \frac{(n-1)*(n-2)*\dots*(1)*(1)!}{n!} = \frac{1}{n} \\
\sum_{i=1}^{n-1} P_{t=i\alpha} &= \sum_{s=1}^{n-1} \frac{n-s}{n} \\
\sum_{i=1}^{n} F_i^L &= \sum_{s=1}^{n-1} \frac{n-s}{n} \qquad \textbf{(3.7)}
\end{aligned}
$$

Since any packet accommodated by OBMS will not be dropped by SQSP, there is no packet drops in SQSP. Thus, the number of packet drops experienced in SQSP buffer should be taken as zero in the following calculation.

$$
\begin{aligned}
\sum_{i=1}^{n} F_i &= \sum_{i=1}^{n} (F_i^L + F_i^D) \\
&= \sum_{i=1}^{n} F_i^L \\
&= \sum_{s=1}^{n-1} \frac{n-s}{n} \\
&= \frac{n-1}{n} + \frac{n-2}{n} + \frac{n-3}{n} + \dots + \frac{1}{n} \\
&= \frac{1}{n} * \left( \frac{n*(n-1)}{2} \right) \\
&= \frac{n-1}{2} \qquad \textbf{(3.8)}
\end{aligned}
$$

According to the Eq. (3.8), it is clearly seen that the expected cost of SQSP strongly depends on the buffer size. Thus, the bigger size of the buffer means that there are more packet losses. Moreover, since there is no packet differentiation in SQSP, these packet losses are diffused to all priority classes equally. Therefore, the expected high priority packet loss that could be experienced in two priority based SQSP is equal to half of the equation given with Eq. (3.8).

### 3.2.2 MQMP

The next analysis is about MQMP. In MQMP solution, packets are accommodated in FIFO manner as in SQSP, but in this time packets are differentiated with their priorities and packets with highest priority are always sent first. The pseudocode of this solution is given with Fig. 3.3.

```
procedure MQMP
    if pkt is received or generated then
        if Q[pkt.priority].size ≤ Max then
            Q[pkt.priority].enqueu(pkt);
            return true;
        else
            pkt = null;                                  ▹ packet is dropped
            return false;                ▹ the buffer is full for this priority
        end if
    end if
    if medium is ready for sending packet then
        for priority = "Highest" to "Lowest" do
            if Q[priority].size ≥ Min then
                pkt = Q[priority].dequeu();
                return true;
            end if
        end for
        return false;
    end if
end procedure
```

**Figure 3.3** MQMP buffer management algorithm

During MQMP analysis, it is assumed that the size of the MQMP buffer is 2 pockets as in SQSP analysis. So, we have a MQMP buffer with 2 priority queues and each

queue hold at most 1 packet at any one time. Supposing that there are two packets labeled with X, Y and it is known that the OBMS accommodates these two packets at the right positions on the buffer and deliver them within their timeout limits. However, MQMP schedules high priority packets in front of low priority ones. Thus, for 2 priority based MQMP buffer, the high priority packet never experiences a packet loss, while the low priority packet could experience a packet loss due to the packet's timeout limitation. So, we have 0.25 expected low priority packet loss for 2 sized MQMP buffer, if packets are in different priorities. But what happens if the packets have the same priorities? In this case, one of two packets is always dropped because of the lack of free space on the related priority queue. So, we have 0.5 expected packet drops for 2 sized MQMP buffer and these drops are diffused to all priority classes equally. The basic MQMP analysis based on two different priorities can be expanded to buffer with size of *n*:

The high priority packet loss experienced in MQMP buffer can be calculated with the help of the intuition used in SQSP analysis. The total buffer space on the sensor node is shared equally between two different priority queues. So, we have n/2 part of the buffer for high priority packets and this part is located in front of the buffer.

- A high priority packet $P_{t=\alpha}$ which is accommodated in $C_1$ by OBMS could be in $C_2$, $C_3$, ..., $C_{n/2}$ pockets in MQMP. If it was so, this packet would be lost. Thus, the expected high priority packet loss for $P_{t=\alpha}$ can be calculated as:

$$\left(\frac{n}{2}-1\right)*\frac{(n-1)!}{\mathrm{n!}}=\left(\frac{n}{2}-1\right)*\frac{1}{\mathrm{n}} \qquad \textbf{(3.9)}$$

- A high priority packet $P_{t=2\alpha}$ which is accommodated in $C_2$ by OBMS could be in $C_3$, $C_4$, ..., $C_{n/2}$ pockets in MQMP. If it was so, this packet would be lost. Thus, the expected high priority packet loss for $P_{\mathrm{t}=2\alpha}$ can be calculated as:

$$\left(\frac{n}{2}-2\right)*\frac{(n-1)!}{\mathrm{n!}}=\left(\frac{n}{2}-2\right)*\frac{1}{\mathrm{n}} \qquad \textbf{(3.10)}$$

- A high priority packet $P_{t=3\alpha}$ which is accommodated in $C_3$ by OBMS could be in $C_4$, $C_5$, ..., $C_{n/2}$ pockets in MQMP. If it was so, this packet would be lost. Thus, the expected high priority packet loss for $P_{t=3\alpha}$ can be calculated as:

$$\left(\frac{n}{2}-3\right)*\frac{(n-1)!}{\mathrm{n!}}=\left(\frac{n}{2}-3\right)*\frac{1}{\mathrm{n}} \qquad \textbf{(3.11)}$$

- If the same procedure is applied to all pockets on the buffer, sum of the expected high priority packet losses that could be experienced in each pocket can be calculated as:

$$\begin{aligned}
\mathrm{P}_{t=\alpha} &= \left(\frac{n}{2}-1\right)*\frac{(n-1)!}{\mathrm{n!}}=\left(\frac{n}{2}-1\right)*\frac{1}{\mathrm{n}}\\
\mathrm{P}_{t=2\alpha} &= \left(\frac{n}{2}-2\right)*\frac{(n-1)!}{\mathrm{n!}}=\left(\frac{n}{2}-2\right)*\frac{1}{\mathrm{n}}\\
\mathrm{P}_{t=3\alpha} &= \left(\frac{n}{2}-3\right)*\frac{(n-1)!}{\mathrm{n!}}=\left(\frac{n}{2}-3\right)*\frac{1}{\mathrm{n}}\\
. &\quad \ldots\\
. &\quad \ldots\\
. &\quad \ldots\\
\mathrm{P}_{t=(n/2-2)\alpha} &= (2)*\frac{(n-1)!}{\mathrm{n!}}=(2)*\frac{1}{\mathrm{n}}\\
\mathrm{P}_{t=(n/2-1)\alpha} &= (1)*\frac{(n-1)!}{\mathrm{n!}}=\frac{1}{\mathrm{n}}\\
\sum_{i=1}^{n/2}P_{t=i\alpha} &= \sum_{i=1}^{n/2}\left(\frac{n}{2}-i\right)*\frac{(n-1)!}{\mathrm{n!}}=\sum_{i=1}^{n/2}\left(\frac{n}{2}-i\right)*\frac{1}{\mathrm{n}}\\
\sum_{i=1}^{n/2}F_i^{Lh} &= \sum_{i=1}^{n/2}\left(\frac{n}{2}-i\right)*\frac{(n-1)!}{\mathrm{n!}}=\sum_{i=1}^{n/2}\left(\frac{n}{2}-i\right)*\frac{1}{\mathrm{n}} \qquad \textbf{(3.12)}
\end{aligned}$$

Since the first half of the buffer is used for the high priority packets in two priority based MQMP buffer, the high priority packet losses can occur just on this part of the buffer. Therefore, the calculation of the high priority packet losses on this MQMP buffer can be continued as shown in below:

$$\begin{aligned}\sum_{i=1}^{n} F_i^{Lh} &= \sum_{i=1}^{n/2} F_i^{Lh} \\ &= \sum_{i=1}^{n/2}\left(\frac{n}{2}-i\right)*\frac{1}{\mathrm{n}} \\ &= \frac{1}{n}*\sum_{i=1}^{n/2}\left(\frac{n}{2}-i\right) \\ &= \frac{1}{n}*\sum_{i=1}^{n/2}\frac{n}{2}-\frac{1}{n}*\sum_{i=1}^{n/2} i \\ &= \frac{n}{4}-\frac{n+2}{8} \\ &= \frac{n-2}{8}\end{aligned} \quad \textbf{(3.13)}$$

According to the analyzed two priority based MQMP buffer, the total buffer space on the sensor node is shared equally between two different priority queues and the low priority packets are located at the back half of the buffer.

- Low priority packets $P_{t=\alpha}$, $P_{t=2\alpha}$, …, $P_{t=(n/2)\alpha}$ accommodated in $C_1$, $C_2$, ..., $C_{n/2}$ by OBMS could be in $C_{(n/2)+1}$, $C_{(n/2)+2}$, ..., $C_n$ pockets in MQMP. If it was so, these packets would be lost. Thus, the expected packet loss for low priority packets $P_{t=\alpha}$, $P_{t=2\alpha}$, …, $P_{t=(n/2)\alpha}$ can be calculated as:

$$\begin{aligned}\mathrm{P}_{t=\alpha} &= (n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!}=\frac{1}{2} \\ \mathrm{P}_{t=2\alpha} &= (n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!}=\frac{1}{2} \\ \mathrm{P}_{t=3\alpha} &= (n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!}=\frac{1}{2} \\ . & \quad \ldots \\ . & \quad \ldots \\ . & \quad \ldots \\ \mathrm{P}_{t=(n/2-1)\alpha} &= (n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!}=\frac{1}{2} \\ \mathrm{P}_{t=(n/2)\alpha} &= (n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!}=\frac{1}{2} \\ \sum_{i=1}^{n/2} P_{t=i\alpha} &= \sum_{i=1}^{n/2}(n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!} \\ \sum_{i=1}^{n/2} F_i^{Ll} &= \sum_{i=1}^{n/2}(n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!}\end{aligned} \quad \textbf{(3.14)}$$

The calculation of the low priority packet losses in two priority based MQMP buffer is composed of two steps, the first one of which is given in below with Eq. (3.15) and the second will be given in the following with Eq. (3.20):

$$\sum_{i=1}^{n} F_i^{Ll} = \sum_{i=1}^{n/2} F_i^{Ll} + \sum_{i=\frac{n}{2}+1}^{n} F_i^{Ll}$$
$$\sum_{i=1}^{n/2} F_i^{Ll} = \left((n-1)*(n-2)*\ldots*\left(n-\frac{\mathrm{n}}{2}\right)*\left(n-\frac{\mathrm{n}}{2}\right)!*\frac{1}{\mathrm{n}!}\right)*\frac{n}{2}$$
$$= \left(\frac{1}{2}\right)*\frac{\mathrm{n}}{2} = \frac{n}{4} \qquad \textbf{(3.15)}$$

- A low priority packet $P_{t\,=\,(n/2)\alpha+1}$ which is accommodated in $C_{(n/2)+1}$ by OBMS could be in $C_{(n/2)+2}$, $C_{(n/2)+3}$, ..., $C_n$ pockets in MQMP. If it was so, this packet would be lost. Thus, the expected low priority packet loss for $P_{t\,=\,(n/2)\alpha+1}$ can be calculated as:

$$\left(\frac{n}{2}-1\right)*(n-1)!*\frac{1}{\mathrm{n}!} \qquad \textbf{(3.16)}$$

- A low priority packet $P_{t\,=\,(n/2)\alpha+2}$ which is accommodated in $C_{(n/2)+2}$ by OBMS could be in $C_{(n/2)+3}$, $C_{(n/2)+4}$, ..., $C_n$ pockets in MQMP. If it was so, this packet would be lost. Thus, the expected low priority packet loss for $P_{t\,=\,(n/2)\alpha+2}$ can be calculated as:

$$\left(\frac{n}{2}-2\right)*(n-1)!*\frac{1}{\mathrm{n}!} \qquad \textbf{(3.17)}$$

- A low priority packet $P_{t\,=\,(n/2)\alpha+3}$ which is accommodated in $C_{(n/2)+3}$ by OBMS could be in $C_{(n/2)+4}$, $C_{(n/2)+5}$, ..., $C_n$ pockets in MQMP. If it was so, this packet would be lost. Thus, the expected low priority packet loss for $P_{t\,=\,(n/2)\alpha+3}$ can be calculated as:

$$\left(\frac{n}{2}-3\right)*(n-1)!*\frac{1}{\mathrm{n}!} \qquad \textbf{(3.18)}$$

- If this goes on, the expected packet loss for low priority packets $P_{t=(n/2)\alpha+1}$, $P_{t=(n/2)\alpha+2}$, $P_{t=(n/2)\alpha+3}$, … , $P_{t=(n)\alpha}$ can be calculated as:

$$
\begin{aligned}
P_{t=(n/2+1)\alpha} &= \left(\frac{n}{2}-1\right) * (n-1)! * \frac{1}{n!} \\
P_{t=(n/2+2)\alpha} &= \left(\frac{n}{2}-2\right) * (n-1)! * \frac{1}{n!} \\
P_{t=(n/2+3)\alpha} &= \left(\frac{n}{2}-3\right) * (n-1)! * \frac{1}{n!} \\
. & \quad \dots \\
. & \quad \dots \\
. & \quad \dots \\
P_{t=(n-2)\alpha} &= (2) * (n-1)! * \frac{1}{n!} \\
P_{t=(n-1)\alpha} &= (1) * (n-1)! * \frac{1}{n!} \\
\sum_{i=\frac{n}{2}+1}^{n-1} P_{t=i\alpha} &= \sum_{i=\frac{n}{2}+1}^{n-1} (n-i) * \frac{1}{n} \\
\sum_{i=\frac{n}{2}+1}^{n} F_i^{Ll} &= \sum_{i=\frac{n}{2}+1}^{n-1} (n-i) * \frac{1}{n}
\end{aligned}
\tag{3.19}
$$

The second step of the calculation of low priority packet losses experienced in two priority based MQMP buffer is completed as in shown below:

$$
\begin{aligned}
\sum_{i=1}^{n} F_i^{Ll} &= \sum_{i=1}^{n/2} F_i^{Ll} + \sum_{i=\frac{n}{2}+1}^{n} F_i^{Ll} \\
\sum_{i=\frac{n}{2}+1}^{n} F_i^{Ll} &= \left(\left(\frac{n}{2}-1\right) + \left(\frac{n}{2}-2\right) + \left(\frac{n}{2}-3\right) + \cdots + (1)\right) * \frac{1}{n} \\
&= \frac{n-2}{8}
\end{aligned}
\tag{3.20}
$$

As high and low priority packet losses on the MQMP buffer has been calculated, there is one thing left is the calculation of the sum of all packet losses on the buffer. Thus, sum of the expected packet losses that could be experienced in each pocket in MQMP buffer is given in below with Eq. (3.21). Therefore, we can complete the calculation as in given below:

$$\begin{aligned}\sum_{i=1}^{n} F_i^L &= \sum_{i=1}^{n} F_i^{Lh} + \sum_{i=1}^{n} F_i^{Ll} \\ &= \sum_{i=1}^{n} F_i^{Lh} + \sum_{i=1}^{n/2} F_i^{Ll} + \sum_{i=\frac{n}{2}+1}^{n} F_i^{Ll} \\ &= \left(\frac{n-2}{8}\right) + \left(\frac{n}{4}\right) + \left(\frac{n-2}{8}\right) \\ &= \frac{n-1}{2} \end{aligned} \tag{3.21}$$

While keeping in mind the OBMS definition, it is clearly seen that there are not any dropped packets in two priority based MQMP buffer, if the number of arriving low and high priority packets are equal to each other and they are less than the half of *n*. Otherwise, packets overflowing from their related priority queues are dropped by the buffer management mechanism of MQMP. In accordance with this reasoning, the expected high priority packet drops that could be experienced in two priority based MQMP buffer can be calculated if the number of packet drops and its probability is known in advance.

Taking into account that at most n/2 packets can be overflowed in two priority based MQMP buffer, the total number of packets overflowed from related priority queues can be calculated as:

- If $\frac{n}{2} + 1$ packets are in the same priority, 1 packet is overflowed from related priority queue. The expected packet drop rate for this case can be given as:

$$1 * \binom{n}{\frac{n}{2} + 1} * \frac{1}{2^n} \tag{3.22}$$

- If $\frac{n}{2}+2$ packets are in the same priority, 2 packets are overflowed from related priority queue. The expected packet drop rate for this case can be given as:

$$2 * \binom{n}{\frac{n}{2}+2} * \frac{1}{2^n} \tag{3.23}$$

- If $\frac{n}{2}+3$ packets are in the same priority, 3 packets are overflowed from related priority queue. The expected packet drop rate for this case can be given as:

$$3 * \binom{n}{\frac{n}{2}+3} * \frac{1}{2^n} \tag{3.24}$$

- If same procedure is applied until reach n packets, the expected number of packets overflowed from a priority queue in total can be calculated as:

$$\begin{aligned}
\sum_{i=1}^{n/2} F_i^D &= 0 \\
F_{\frac{n}{2}+1}^D &= 1 * \binom{n}{\frac{n}{2}+1} * \frac{1}{2^n} \\
F_{\frac{n}{2}+2}^D &= 2 * \binom{n}{\frac{n}{2}+2} * \frac{1}{2^n} \\
F_{\frac{n}{2}+3}^D &= 3 * \binom{n}{\frac{n}{2}+3} * \frac{1}{2^n} \\
. & \quad \ldots \\
. & \quad \ldots \\
. & \quad \ldots \\
F_n^D &= \frac{n}{2} * \binom{n}{n} * \frac{1}{2^n} \\
\sum_{i=1}^{n} F_i^D &= \left(\sum_{i=1}^{n/2} i * \binom{n}{\frac{n}{2}+i}\right) * \left(\frac{1}{2^n}\right)
\end{aligned} \tag{3.25}$$

Thus, the cost of the two priority based MQMP buffer can be given as:

$$\sum_{i=1}^{n} F_i = \sum_{i=1}^{n} (F_i^L + F_i^D)$$
$$= \left(\frac{n-1}{2}\right) + 2 * \left(\sum_{i=1}^{\frac{n}{2}} \frac{i}{2^n} * \binom{n}{\frac{n}{2}+i}\right) \quad \textbf{(3.26)}$$

As can be seen in Eq. (3.8) and Eq. (3.26), the expected high priority packet loss is relatively closer for low buffer sizes. However, MQMP suffers from packet drops due to the reduced buffer capacities. As the ratio between high and low priority packets on the buffer gets away from 1, the performance of the MQMP falls seriously. This means that MQMP based solutions could show unexpected poor performances due to the fragmented buffer space of the sensor nodes and the imbalance between priorities of incoming packets. On the other hand, MQMP gives somehow a priority to higher priority packets and therefore, compared to SQSP, MQMP based solutions has a lower total cost in terms of high priority packet transmission. This does not change even if the same number of packets are served by these two buffer management solutions.

### 3.2.1 SQMP

The last analysis is about our proposed solution SQMP. In SQMP, packets are not accommodated in FIFO manner and in this solution packets are differentiated and prioritized according to their priorities. The details of this solution and the pseudocode of SQMP are given in below with Fig. 3.4.

```
procedure SQMP
    if pkt is received or generated then
        if Q.size ≤ Max then                          ▹ the buffer is not full
            for i ← 1, Q.size do
                if pkt.priority > Q[i].priority then
                    Q[i].insert(pkt);  ▹ higher priority packet is inserted
                    return true;
                end if
            end for
            Q.enqueu(pkt);
            return true;
        else                                          ▹ the buffer is full
            for i ← 1, n do
                if pkt.priority > Q[i].priority then
                    Q[i] = pkt;        ▹ higher priority packet is buffered
                    return true;
                end if
            end for
            pkt = null;                ▹ coming new packet is dropped
            return false;
        end if
    end if
    if medium is ready for sending packet then
        if Q.size ≥ Min then
            pkt = Q.dequeu();
            return true;
        else
            return false;                             ▹ the buffer is empty
        end if
    end if
end procedure
```

**Figure 3.4** SQMP buffer management algorithm

The assumptions made in SQSP and MQMP analysis, hold also for SQMP. So during SQMP analysis, it is assumed that there is a SQMP buffer which has 2 pockets and supports 2 different priorities. It is obvious that this buffer could hold at most 2 packets at any one time. Let's suppose there are two packets labeled with X and Y. It is known that the OBMS accommodates these two packets at the right positions on the buffer and delivers them within their timeout limits. If there are two packets with two different priorities, three different cases can occur: The packets, X and Y, could belong to either same priority class or different priority classes. In case the packets are in the

same priority class, both packets should be either high priority or low priority. So, it can be clearly seen that there are three different cases in our hands that need more explanation.

1. In the first case, suppose both X and Y are high priority packets (term a) and they are accommodated in $C_1$ and $C_2$ pockets respectively by OBMS. However, SQMP could accommodate these 2 high priority packets in reverse order (term b). If it was so, the packet X would be lost. There is no high priority packet loss in SQMP except for this case. Thus, the expected high priority packet loss in 2 sized and 2 priority-based SQMP buffer is equal to 0.125 as in shown below:

$$\underbrace{\left(\frac{1}{2} * \frac{1}{2}\right)}_{\text{term a}} * \underbrace{\left(\frac{1}{2}\right)}_{\text{term b}} = \frac{1}{8} = 0.125 \qquad \textbf{(3.27)}$$

2. In the second case, suppose one of X and Y is low priority packet (term a) and the low priority packet is accommodated in $C_1$ by OBMS. However, SQMP will accommodate high priority packets in front of low priority ones. So, the low priority packet would be lost in SQMP if it was accommodated in $C_1$ (term b) by OBMS. From here, the expected low priority packet loss experienced in SQMP buffer for this case is equal to 0.25 as in shown below:

$$\underbrace{\left(\frac{1}{2}\right)}_{\text{term a}} * \underbrace{\left(\frac{1}{2}\right)}_{\text{term b}} = \frac{1}{4} \qquad \textbf{(3.28)}$$

3. In the third case, suppose both X and Y are low priority packets (term a) and they are accommodated in $C_1$ and $C_2$ pockets respectively by OBMS. However, SQMP could accommodate these 2 low priority packets in reverse order (term b). If it was so, the packet X would be lost. From here, the expected low priority packet loss experienced in SQMP buffer for this case is equal to 0.125 as in shown below:

$$\underbrace{\left(\frac{1}{2} * \frac{1}{2}\right)}_{\text{term a}} * \underbrace{\left(\frac{1}{2}\right)}_{\text{term b}} = \frac{1}{8} = 0.125 \qquad \textbf{(3.29)}$$

For 2 sized and 2 priority-based SQMP buffer, the total low priority packet loss is 0.25+0.125 = 0.375 and the total packet loss is 0.375 + 0.125 = 0.5. In the following, $F_i^{Ll}$ and $F_i^{Lh}$ stand for low and high priority packets respectively which are lost in SQMP. The number of packet drops is taken as zero for SQMP because there is no such packet which is accommodated by OBMS but dropped by SQMP. Our SQMP analysis can be expanded to buffer with size of *n*:

- First, the analysis is expanded to size of *n* for high priority packets. A high priority packet $P_{t=\alpha}$ which is accommodated in $C_1$ by OBMS could be in $C_2$, $C_3$, ..., $C_n$ pockets in SQMP under different circumstances such as:
  - Assuming that 2 of *n* packets are high priority packets (term a) and one of these high priority packets is accommodated in $C_1$ (term b) by OBMS. If this high priority packet was accommodated in $C_2$ pocket (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{2} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{2}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{1}{2}\right)}_{\text{term c}} \qquad \textbf{(3.30)}$$

  - Assuming that 3 of *n* packets are high priority packets (term a) and one of these high priority packets is accommodated in $C_1$ (term b) by OBMS. If this high priority packet was accommodated in $C_2$, $C_3$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{3} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{3}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{2}{3}\right)}_{\text{term c}} \qquad \textbf{(3.31)}$$

  - Assuming that k of *n* packets (k ≤ n) are high priority packets (term a) and one of these high priority packets is accommodated in $C_1$ (term b) by

OBMS. If this high priority packet was accommodated in $C_2$, $C_3$,..., $C_k$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{k} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{k}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{k-1}{k}\right)}_{\text{term c}} \quad \textbf{(3.32)}$$

- A high priority packet $P_{t=2\alpha}$ which is accommodated in $C_2$ by OBMS could be in different pockets in SQMP. The possible packet losses in SQMP are as given below:
  - Assuming that 3 of *n* packets are high priority packets (term a) and one of these high priority packets is accommodated in $C_2$ (term b) by OBMS. If this high priority packet was accommodated in $C_3$ pocket (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{3} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{3}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{1}{3}\right)}_{\text{term c}} \quad \textbf{(3.33)}$$

  - Assuming that 4 of *n* packets are high priority packets (term a) and one of these high priority packets is accommodated in $C_2$ (term b) by OBMS. If this high priority packet was accommodated in $C_3$, $C_4$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{4} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{4}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{2}{4}\right)}_{\text{term c}} \quad \textbf{(3.34)}$$

  - Assuming that k of *n* packets ($k \leq n$) are high priority packets (term a) and one of these high priority packets is accommodated in $C_2$ (term b) by OBMS. If this high priority packet was accommodated in $C_3$, $C_4$,..., $C_k$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{k} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{k}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{k-2}{k}\right)}_{\text{term c}} \tag{3.35}$$

- If the same procedure is applied to all pockets on the buffer, the sum of the expected high priority packet losses that could be experienced in each pocket is equal to:

$$\begin{aligned}
P_{t=\alpha} &= \sum_{k=2}^{n}\left(\binom{n}{k} * \frac{1}{2^n}\right) * \left(\frac{k}{n}\right) * \left(\frac{k-1}{k}\right) \\
P_{t=2\alpha} &= \sum_{k=3}^{n}\left(\binom{n}{k} * \frac{1}{2^n}\right) * \left(\frac{k}{n}\right) * \left(\frac{k-2}{k}\right) \\
P_{t=3\alpha} &= \sum_{k=4}^{n}\left(\binom{n}{k} * \frac{1}{2^n}\right) * \left(\frac{k}{n}\right) * \left(\frac{k-3}{k}\right) \\
. & \quad \dots \\
. & \quad \dots \\
. & \quad \dots \\
P_{t=(n-2)\alpha} &= \sum_{k=n-1}^{n}\left(\binom{n}{k} * \frac{1}{2^n}\right) * \left(\frac{k}{n}\right) * \left(\frac{k-(n-2)}{k}\right) \\
P_{t=(n-1)\alpha} &= \sum_{k=n}^{n}\left(\binom{n}{k} * \frac{1}{2^n}\right) * \left(\frac{k}{n}\right) * \left(\frac{k-(n-1)}{k}\right) \\
\sum_{i=1}^{n-1} P_{t=i\alpha} &= \sum_{s=1}^{n-1}\sum_{k=s+1}^{n}\left(\binom{n}{k} * \frac{1}{2^n}\right) * \left(\frac{k}{n}\right) * \left(\frac{k-s}{k}\right) \\
\sum_{i=1}^{n} F_i^{Lh} &= \sum_{s=1}^{n-1}\sum_{k=s+1}^{n}\left(\binom{n}{k} * \frac{k-s}{n*2^n}\right)
\end{aligned} \tag{3.36}$$

High priority packet loss in the SQMP buffer is given with the Eq. (3.36). In the following, we will try to simplify this equation by rewriting it in an extended form. But, before proceeding to look at the extended form of the equation more closely, it is important to clarify simplification steps of the equation in order to give better understanding. In each simplification step, the terms in not simple form in the given equation are tried to be simplified by extracting such terms from the main equation and then giving a solution for them.

$$
\begin{array}{rcccccccccccc}
P_{t=\alpha} & = & \frac{\binom{n}{2}*1}{n*2^n} & + & \frac{\binom{n}{3}*2}{n*2^n} & + & \frac{\binom{n}{4}*3}{n*2^n} & + & \frac{\binom{n}{5}*4}{n*2^n} & + & \frac{\binom{n}{6}*5}{n*2^n} & + & \dots & + & \frac{\binom{n}{n}*(n-1)}{n*2^n} \\
P_{t=2\alpha} & = & \frac{\binom{n}{3}*1}{n*2^n} & + & \frac{\binom{n}{4}*2}{n*2^n} & + & \frac{\binom{n}{5}*3}{n*2^n} & + & \frac{\binom{n}{6}*4}{n*2^n} & + & \dots & + & \frac{\binom{n}{n}*(n-2)}{n*2^n} & & | \\
P_{t=3\alpha} & = & \frac{\binom{n}{4}*1}{n*2^n} & + & \frac{\binom{n}{5}*2}{n*2^n} & + & \frac{\binom{n}{6}*3}{n*2^n} & + & \dots & + & \frac{\binom{n}{n}*(n-3)}{n*2^n} & & | & & | \\
. & = & \dots & + & \dots & + & \dots & + & \dots & & | & & | & & | \\
. & = & \dots & + & \dots & + & \dots & + & \dots & & | & & | & & | \\
. & = & \dots & + & \dots & + & \dots & + & \dots & & | & & | & & | \\
P_{t=(n-2)\alpha} & = & \frac{\binom{n}{n-1}*1}{n*2^n} & + & \frac{\binom{n}{n}*2}{n*2^n} & & | & & | & & | & & | & & | \\
P_{t=(n-1)\alpha} & = & \frac{\binom{n}{n}*1}{n*2^n} & & | & & \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots & & & & & & & & \frac{\binom{n}{n}*1}{n*2^n} \\
 & & \underbrace{\quad}_{term\ 1} & & \underbrace{\quad}_{term\ 2} & & \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{term\ \dots} & & & & & & & & \underbrace{\quad}_{term\ n-1}
\end{array}
\tag{3.37}
$$

In the extended form given above, each term which is identified with a number between 1 to n-1 corresponds the sum of the vertical items in the related column. They are re-expressed as usual form in below:

$$
\begin{aligned}
\text{term 1} &= \frac{1}{n*2^n} * 1 * \left(\binom{n}{2} + \binom{n}{3} + \cdots + \binom{n}{n}\right) \\
\text{term 2} &= \frac{1}{n*2^n} * 2 * \left(\binom{n}{3} + \binom{n}{4} + \cdots + \binom{n}{n}\right) \\
\text{term 3} &= \frac{1}{n*2^n} * 3 * \left(\binom{n}{4} + \binom{n}{5} + \cdots + \binom{n}{n}\right) \\
. & \quad \dots \\
. & \quad \dots \\
. & \quad \dots \\
\text{term (n-2)} &= \frac{1}{n*2^n} * (n-2) * \left(\binom{n}{n-1} + \binom{n}{n}\right) \\
\text{term (n-1)} &= \frac{1}{n*2^n} * (n-1) * \left(\binom{n}{n}\right)
\end{aligned}
\tag{3.38}
$$

We need two important facts which are given in below with Eq. (3.39) and Eq. (3.43) to continue the simplification of the equation given with Eq. (3.36).

Taking into account the fact:

$$2^n = \binom{n}{0} + \binom{n}{1} + \binom{n}{2} + \cdots \binom{n}{n} \tag{3.39}$$

Each term can be re-expressed in such a way as in shown below and the sum of the all terms can be also seen at the end of the new expression.

$$\begin{aligned}
\text{term 1} &= \frac{1}{n*2^n} * 1 * \left(2^n - \binom{n}{0} - \binom{n}{1}\right) + \\
\text{term 2} &= \frac{1}{n*2^n} * 2 * \left(2^n - \binom{n}{0} - \binom{n}{1} - \binom{n}{2}\right) + \\
\text{term 3} &= \frac{1}{n*2^n} * 3 * \left(2^n - \binom{n}{0} - \binom{n}{1} - \binom{n}{2} - \binom{n}{3}\right) + \\
. & \qquad \ldots \\
. & \qquad \ldots \\
\text{term (n-2)} &= \frac{1}{n*2^n} * (n-2) * \left(2^n - \binom{n}{0} - \binom{n}{1} - \cdots - \binom{n}{n-2}\right) + \\
\text{term (n-1)} &= \frac{1}{n*2^n} * (n-1) * \left(2^n - \binom{n}{0} - \binom{n}{1} - \cdots - \binom{n}{n-1}\right) \\
\sum_{i=1}^{n-1} term\ i &= \frac{1}{n*2^n} * \sum_{s=1}^{n-1}\left(s * 2^n - s * \sum_{r=0}^{s}\binom{n}{r}\right) \\
&= \frac{1}{n*2^n} * \left(\frac{n*(n-1)}{2} * 2^n - \sum_{s=1}^{n-1} s * \sum_{r=0}^{s}\binom{n}{r}\right) \\
&= \underbrace{\frac{(n-1)}{2}}_{term\ d} - \underbrace{\frac{1}{n*2^n}}_{term\ e} * \underbrace{\sum_{s=1}^{n-1}\sum_{r=0}^{s} s * \binom{n}{r}}_{\text{term f}}
\end{aligned} \tag{3.40}$$

The Eq. (3.40) is composed of 3 terms and the one of them has needed a more simplification. The simplifying steps of the relevant term are given in below:

$$\begin{aligned}
\text{term f} = \quad & 1 * \left[\binom{n}{0} + \binom{n}{1}\right] + \\
\rightarrow \quad & 2 * \left[\binom{n}{0} + \binom{n}{1} + \binom{n}{2}\right] + \\
\rightarrow \quad & 3 * \left[\binom{n}{0} + \binom{n}{1} + \binom{n}{2} + \binom{n}{3}\right] + \\
\rightarrow \quad & \ldots + \ldots + \ldots + \ldots + \\
\rightarrow \quad & \ldots + \ldots + \ldots + \ldots + \\
\rightarrow \quad & \ldots + \ldots + \ldots + \ldots + \\
\rightarrow \quad & \underbrace{(n-1) * \left[\binom{n}{0}\right.}_{term\ f.1} + \underbrace{\binom{n}{1}}_{term\ f.2} + \underbrace{\binom{n}{2}}_{term\ f.3} + \underbrace{\binom{n}{3}}_{term\ f.4} + \ldots + \underbrace{\left.\binom{n}{n-1}\right]}_{term\ f.n}
\end{aligned}$$

**(3.41)**

The sum of the $term\ f.1, term\ f.2, term\ f.3, \dots, term\ f.n$ is equal to $term\ f$. Therefore, $term\ f = \sum_{i=1}^{n} term\ \mathrm{f}.i$ is absolutely true according to the definition of the $term\ f$. The simplification steps of the $term\ f$ and the new form of each its components can be seen in below:

$$
\begin{aligned}
\text{term f.1} &= \frac{n*(n-1)}{2} * \binom{n}{0} \\
\text{term f.2} &= \frac{n*(n-1)}{2} * \binom{n}{1} \\
\text{term f.3} &= \left(\frac{n*(n-1)}{2} - 1\right) * \binom{n}{2} \\
\text{term f.4} &= \left(\frac{n*(n-1)}{2} - 3\right) * \binom{n}{3} \\
\text{term f.5} &= \left(\frac{n*(n-1)}{2} - 6\right) * \binom{n}{4} \\
. & \quad \dots \\
. & \quad \dots \\
. & \quad \dots \\
\text{term f.n} &= \left(\frac{n*(n-1)}{2} - \frac{(n-1)*(n-2)}{2}\right) * \binom{n}{n-1} \\
\text{term f} &= \frac{n*(n-1)}{2} * \binom{n}{0} + \frac{n*(n-1)}{2} * \binom{n}{1} + \frac{n*(n-1)}{2} * \binom{n}{2} + \frac{n*(n-1)}{2} * \binom{n}{3} \\
&\quad + \dots + \frac{n*(n-1)}{2} * \binom{n}{n-1} + \frac{n*(n-1)}{2} * \binom{n}{n} \\
&\quad - 1 * \binom{n}{2} - 3 * \binom{n}{3} - 6 * \binom{n}{4} - 10 * \binom{n}{5} \\
&\quad - \dots - \frac{(n-1)*(n-2)}{2} * \binom{n}{n-1} - \frac{n*(n-1)}{2} * \binom{n}{n} \\
&= \frac{n*(n-1)}{2} * \left(\binom{n}{0} + \binom{n}{1} + \binom{n}{2} + \dots + \binom{n}{n-1} + \binom{n}{n}\right) - \left(\binom{n}{2} + 3 * \binom{n}{3}\right. \\
&\quad \left. + 6 * \binom{n}{4} + \dots + \frac{(n-1)*(n-2)}{2} * \binom{n}{n-1} + \frac{n*(n-1)}{2} * \binom{n}{n}\right) \\
&= \frac{n*(n-1)}{2} * 2^n - \left(\binom{n}{2} + 3 * \binom{n}{3} + 6 * \binom{n}{4} + \dots + \frac{n*(n-1)}{2} * \binom{n}{n}\right) \\
&= \frac{n*(n-1)}{2} * 2^n - \sum_{s=1}^{n-1} \frac{(s+1)*s}{2} * \binom{n}{s+1} \qquad \textbf{(3.42)}
\end{aligned}
$$

Taking into account the fact:

$$k * \binom{n}{k} = k * \left(\frac{n!}{k! * (n-k)!}\right) = n\left(\frac{(n-1)!}{(k-1)! * (n-k)!}\right) = n\binom{n-1}{k-1} \quad \textbf{(3.43)}$$

$$\begin{aligned}
\text{term f} &= \frac{n*(n-1)}{2} * 2^n - \sum_{s=1}^{n-1} \frac{s}{2} * (s+1) * \binom{n}{s+1} \\
&= \frac{n*(n-1)}{2} * 2^n - \sum_{s=1}^{n-1} \frac{s}{2} * n * \binom{n-1}{s} \\
&= \frac{n*(n-1)}{2} * 2^n - \sum_{s=1}^{n-1} \frac{n}{2} * s * \binom{n-1}{s} \\
&= \frac{n*(n-1)}{2} * 2^n - \sum_{s=1}^{n-1} \frac{n}{2} * (n-1) * \binom{n-2}{s-1} \\
&= \frac{n*(n-1)}{2} * 2^n - \frac{n*(n-1)}{2} * \sum_{s=1}^{n-1} \binom{n-2}{s-1} \\
&= \frac{n*(n-1)}{2} * 2^n - \frac{n*(n-1)}{2} * 2^{(n-2)} \qquad \textbf{(3.44)}
\end{aligned}$$

The simplification of the equation which is given with the Eq. (3.40) can be finalized easily with results that we had in our hands as it shown below:

$$\begin{aligned}
\sum_{i=1}^{n} F_i^{Lh} &= \sum_{i=1}^{n-1} term\ i \\
\sum_{i=1}^{n-1} term\ i &= \underbrace{\frac{(n-1)}{2}}_{term\ d} - \underbrace{\frac{1}{n*2^n}}_{term\ e} * \underbrace{\left(\frac{n*(n-1)}{2} * 2^n - \frac{n*(n-1)}{2} * 2^{(n-2)}\right)}_{term\ f} \\
&= \frac{n-1}{8} \qquad \textbf{(3.45)}
\end{aligned}$$

- Second, the analysis is expanded to size of *n* for low priority packets. The analysis will continue with assuming 1 of *n* packet is low priority packet and this packet could be accommodated in different pockets by SQMP unlike OBMS under different circumstances as follows:
  - Assuming that 1 of *n* packet is low priority packet (term a) and this low priority packet is accommodated in $C_1$ (term b) by OBMS. If this low priority packet was accommodated in $C_2$, $C_3$,…, $C_n$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{1} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{1}{n}\right)}_{\text{term b}} * \underbrace{(1)}_{\text{term c}} \tag{3.46}$$

- Assuming that 1 of *n* packet is low priority packet (term a) and this low priority packet is accommodated in $C_2$ (term b) by OBMS. If this low priority packet was accommodated in $C_3$, $C_4$,…, $C_n$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{1} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{1}{n}\right)}_{\text{term b}} * \underbrace{(1)}_{\text{term c}} \tag{3.47}$$

- Assuming that 1 of *n* packet is low priority packet (term a) and this low priority packet is accommodated in $C_{k<n}$ (term b) by OBMS. If this low priority packet was accommodated in $C_{k+1}$, $C_{k+2}$,…, $C_n$ pocket (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{1} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{1}{n}\right)}_{\text{term b}} * \underbrace{(1)}_{\text{term c}} \qquad k \leq n-1 \tag{3.48}$$

- Assuming 2 of *n* packet are low priority packets and these packets could be accommodated in different pockets by SQMP unlike OBMS under different circumstances as follows:
  - Assuming that 2 of *n* packets are low priority packet (term a) and one of these low priority packets is accommodated in $C_1$ (term b) by OBMS. If this low priority packet was accommodated in $C_2$, $C_3$,…, $C_n$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{2} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{2}{n}\right)}_{\text{term b}} * \underbrace{(1)}_{\text{term c}} \tag{3.49}$$

- Assuming that 2 of *n* packets are low priority packet (term a) and one of these low priority packets is accommodated in $C_2$ (term b) by OBMS. If this low priority packet was accommodated in $C_3$, $C_4$,…, $C_n$ pockets (term c) by SQMP, it would be lost.

$$\underbrace{\left(\binom{n}{2} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{2}{n}\right)}_{\text{term b}} * \underbrace{(1)}_{\text{term c}} \tag{3.50}$$

- Assuming that 2 of *n* packets are low priority packets (term a) and one of these low priority packets is accommodated in $C_{k<n}$ (term b) by OBMS. If this low priority packet was accommodated in $C_{k+1}$, $C_{k+2}$,…, $C_n$ pockets (term c) by SQMP, it would be lost.

$$\begin{cases} \underbrace{\left(\binom{n}{2} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{2}{n}\right)}_{\text{term b}} * \underbrace{(1)}_{\text{term c}} & k \leq n-2 \\ \underbrace{\left(\binom{n}{2} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{2}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{1}{2}\right)}_{\text{term c}} & n-1 \geq k > n-2 \end{cases} \tag{3.51}$$

- Assuming that s of *n* packets are low priority packets (term a) and one of these low priority packets is accommodated in $C_{k<n}$ (term b) by OBMS. If this low priority packet was accommodated in $C_{k+1}$, $C_{k+2}$,…, $C_n$ pockets (term c) by SQMP, it would be lost.

$$\begin{cases} \underbrace{\left(\binom{n}{s} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{s}{n}\right)}_{\text{term b}} * \underbrace{(1)}_{\text{term c}} & k \leq n-s \\ \underbrace{\left(\binom{n}{s} * \frac{1}{2^n}\right)}_{\text{term a}} * \underbrace{\left(\frac{s}{n}\right)}_{\text{term b}} * \underbrace{\left(\frac{n-k}{s}\right)}_{\text{term c}} & n-1 \geq k > n-s \end{cases} \tag{3.52}$$

- If the same procedure is applied to all pockets on the buffer, the sum of the expected low priority packet losses that could be experienced in each pocket is equal to:

$$
\begin{aligned}
(1)\text{ of n } &\rightarrow \sum_{k=1}^{n-1}\left(\binom{n}{1} * \frac{1}{2^n}\right) * \left(\frac{1}{n}\right) \\
(2)\text{ of n } &\rightarrow \sum_{k=1}^{n-2}\left(\binom{n}{2} * \frac{1}{2^n}\right) * \left(\frac{2}{n}\right) + \sum_{k=n-1}^{n-1}\left(\binom{n}{2} * \frac{1}{2^n}\right) * \left(\frac{2}{n}\right) * \left(\frac{\mathrm{n-k}}{2}\right) \\
(3)\text{ of n } &\rightarrow \sum_{k=1}^{n-3}\left(\binom{n}{3} * \frac{1}{2^n}\right) * \left(\frac{3}{n}\right) + \sum_{k=n-2}^{n-1}\left(\binom{n}{3} * \frac{1}{2^n}\right) * \left(\frac{3}{n}\right) * \left(\frac{n-k}{3}\right) \\
&. \qquad \ldots \\
&. \qquad \ldots \\
&. \qquad \ldots \\
(\text{n-2})\text{ of n } &\rightarrow \sum_{k=1}^{2}\left(\binom{n}{\mathrm{n-2}} * \frac{1}{2^n}\right) * \left(\frac{\mathrm{n-2}}{n}\right) + \sum_{k=3}^{n-1}\left(\binom{n}{\mathrm{n-2}} * \frac{1}{2^n}\right) * \left(\frac{\mathrm{n-2}}{n}\right) * \left(\frac{n-k}{\mathrm{n-2}}\right) \\
(\text{n-1})\text{ of n } &\rightarrow \sum_{k=1}^{1}\left(\binom{n}{\mathrm{n-1}} * \frac{1}{2^n}\right) * \left(\frac{\mathrm{n-1}}{n}\right) + \sum_{k=2}^{n-1}\left(\binom{n}{\mathrm{n-1}} * \frac{1}{2^n}\right) * \left(\frac{\mathrm{n-1}}{n}\right) * \left(\frac{n-k}{\mathrm{n-1}}\right) \\
(\text{n})\text{ of n } &\rightarrow \sum_{k=1}^{n-1}\left(\binom{n}{\mathrm{n}} * \frac{1}{2^n}\right) * \left(\frac{\mathrm{n}}{n}\right) * \left(\frac{n-k}{\mathrm{n}}\right) \\
\sum_{i=1}^{n}(i)\text{ of n } &= \underbrace{\sum_{s=1}^{n}\sum_{k=1}^{n-s}\left(\binom{n}{s} * \frac{1}{2^n}\right) * \left(\frac{s}{n}\right)}_{term\ g} \\
&\quad + \underbrace{\sum_{s=1}^{n}\sum_{k=n-s+1}^{n-1}\left(\binom{n}{s} * \frac{1}{2^n}\right) * \left(\frac{s}{n}\right) * \left(\frac{n-k}{s}\right)}_{term\ h} \\
\sum_{i=1}^{n} F_i^{Ll} &= \underbrace{\sum_{s=1}^{n}\left(\binom{n}{s} * \frac{1}{2^n}\right) * \left(\frac{s}{n}\right) * (n-s)}_{term\ g} \\
&\quad + \underbrace{\sum_{s=1}^{n}\sum_{r=0}^{s-1}\left(\binom{n}{s} * \frac{1}{2^n}\right) * \left(\frac{s}{n}\right) * \left(\frac{r}{s}\right)}_{term\ h}
\end{aligned}
\tag{3.53}
$$

Low priority packet loss in the SQMP buffer is given with Eq. (3.53). This equation is composed of the two terms and the simplification steps of each can be seen in below:

$$
\begin{aligned}
term\ g &= \sum_{s=1}^{n}\left(\frac{n!}{s!*(n-s)!}\right) * \left(\frac{1}{2^n}\right) * \left(\frac{s*(n-s)}{n}\right) \\
&= \sum_{s=1}^{n}\left(\frac{(n-1)!}{(s-1)!*(n-s-1)!}\right) * \left(\frac{1}{2^n}\right) * \left(\frac{n-1}{n-1}\right) \\
&= \sum_{s=1}^{n}\left(\frac{(n-2)!}{(s-1)!*(n-s-1)!}\right) * \left(\frac{n-1}{2^n}\right) \\
&= \sum_{s=1}^{n}\binom{n-2}{s-1} * \left(\frac{n-1}{2^n}\right) \\
&= \frac{n-1}{2^n} * 2^{n-2} \\
&= \frac{n-1}{4}
\end{aligned}
\tag{3.54}
$$

And as in $term\ g$, $term\ h$ can be simplified as:

$$
\begin{aligned}
term\ h &= \sum_{s=1}^{n} \sum_{r=0}^{s-1} \left( \binom{n}{s} * \frac{1}{2^n} \right) * \left( \frac{s}{n} \right) * \left( \frac{r}{s} \right) \\
&= \sum_{s=1}^{n} \sum_{r=0}^{s-1} \left( \binom{n}{s} * \frac{r}{n*2^n} \right) \\
&= \sum_{s=1}^{n} \left( \binom{n}{s} * \frac{1}{n*2^n} * \left( 0 + 1 + 2 + \cdots + (s-1) \right) \right) \\
&= \sum_{s=1}^{n} \left( \binom{n}{s} * \frac{1}{n*2^n} * \left( \frac{s*(s-1)}{2} \right) \right) \\
&= \sum_{s=1}^{n} \left( \left( \frac{n!}{s!*(n-s)!} \right) * \frac{1}{n*2^n} * \frac{s*(s-1)}{2} * \frac{n-1}{n-1} \right) \\
&= \sum_{s=1}^{n} \left( \left( \frac{(n-2)!}{(s-2)!*(n-s)!} \right) * \left( \frac{n-1}{2^{n+1}} \right) \right) \\
&= \sum_{s=1}^{n} \left( \binom{n-2}{s-2} * \left( \frac{n-1}{2^{n+1}} \right) \right) \\
&= \left( \frac{n-1}{2^{n+1}} \right) * 2^{n-2} \\
&= \frac{n-1}{8}
\end{aligned}
\tag{3.55}
$$

Since any packet accommodated by OBMS will not be dropped by SQMP as in SQSP, there are no packet drops in SQMP. For this reason, the number of packet drops experienced in SQMP buffer is equal to zero. Thus, the cost of two priority based SQMP buffer could be given as:

$$
\begin{aligned}
\sum_{i=1}^{n} F_i &= \sum_{i=1}^{n} F_i^L + \sum_{i=1}^{n} F_i^D \\
&= \sum_{i=1}^{n} F_i^L \\
&= \sum_{i=1}^{n} F_i^{Lh} + \sum_{i=1}^{n} F_i^{Ll} \\
&= \left( \frac{n-1}{8} \right) + \left( \frac{n-1}{8} + \frac{n-1}{4} \right) \\
&= \frac{n-1}{2}
\end{aligned}
\tag{3.56}
$$

## 3.3 Problem Formulation and Comparisons

Taking into account the assumptions and constraints given in the first section and the methodology described generally in the second section of this chapter, the problem to which a solution is presented herein is as follows: In view of buffer management solutions, packets may never reach at the sink node due to the lack of empty space on the buffer or the timeout limitations of packets. Thus, it is very important for a buffer management solution proposed for WSNs to use available buffer space in an efficient manner and to provide the necessary prioritization between packets. In other words, the main purpose of a buffer management solution is to minimize the total cost as much as possible. The total cost is equal to sum of the costs of packets that have been lost due the timeliness and dropped due to the lack of free space on the memory. If the cost of a lost packet is denoted by $C_L$ and the cost of a dropped packet is denoted by $C_D$, the problem becomes a minimization problem as in shown below:

$$F = \min \sum (C_L + C_D) \tag{3.57}$$

According to the findings obtained from the analysis which is in the second section of this chapter, it seems that the multi-queue structure causes more packet losses on the buffer in comparison with single-queued one. Although it is known intuitively that the utilization performance of single-queued buffer is better than a multi-queued one, our conceptual model and the analyses reveal this fact more clearly. As we also underlined during analyses, the greatest deficiency of single-queued buffers is that they cannot perform any prioritization between different traffic classes. In order to overcome this deficiency, some strategies have been adopted in SQMP and it has been observed that the methods employed by SQMP for differentiation and prioritization of packets have yielded quite good results. In the following, a sample scenario will be presented for the reader to illustrate the expected packet losses of different buffer management solutions and their rough costs through comparative graphs.

The effects of buffer size on packet losses and packet drops for the examined buffer management solutions could be seen in Fig. 3.5. In this figure, which presents comparative results obtained from mathematical analyses, it is clearly seen that the expected cost for all buffer management solutions strongly depends on the buffer size. Since there are no packet drops, the values obtained from SQSP and SQMP analysis are same as expected and they are better than values observed in MQMP. However, according to Fig. 3.6, which illustrates the relation between buffer size and the costs of different buffer management solutions, the expected cost of SQMP is lower than other two solutions. It should be noted that while drawing this plot, it is assumed that the ratio between the costs of a high priority packet and a low priority packet is equal to $\frac{P_{p=L}}{P_{p=H}} = \frac{1}{2}$ , but it can vary from application to other. For instance, if this ratio is $\frac{P_{p=L}}{P_{p=H}} = \frac{1}{5}$ , the plot to be obtained is shown in Fig 3.7. In other words, it means the lower this ratio, the higher success of our proposed solution will be.

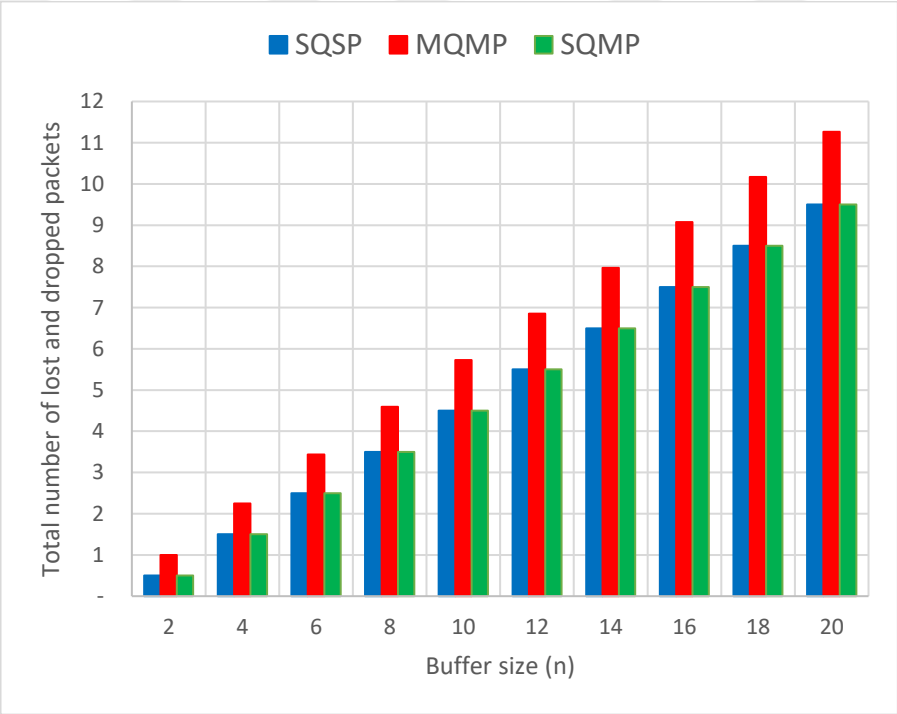


**Figure 3.5** Impact of buffer size on packet loss and packet drops

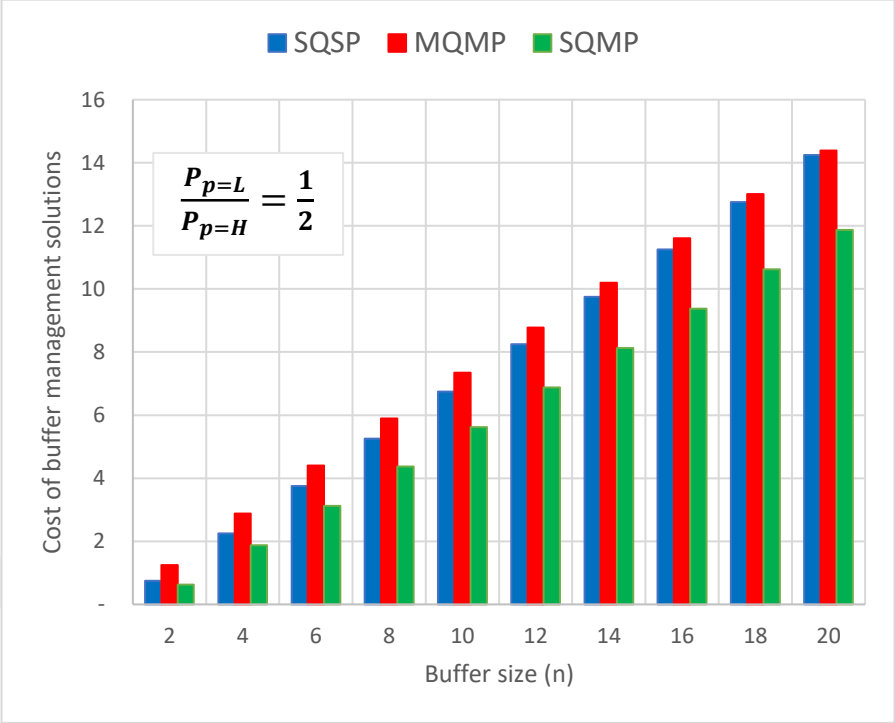


**Figure 3.6** Impact of buffer size on the cost of buffer management (1/2)

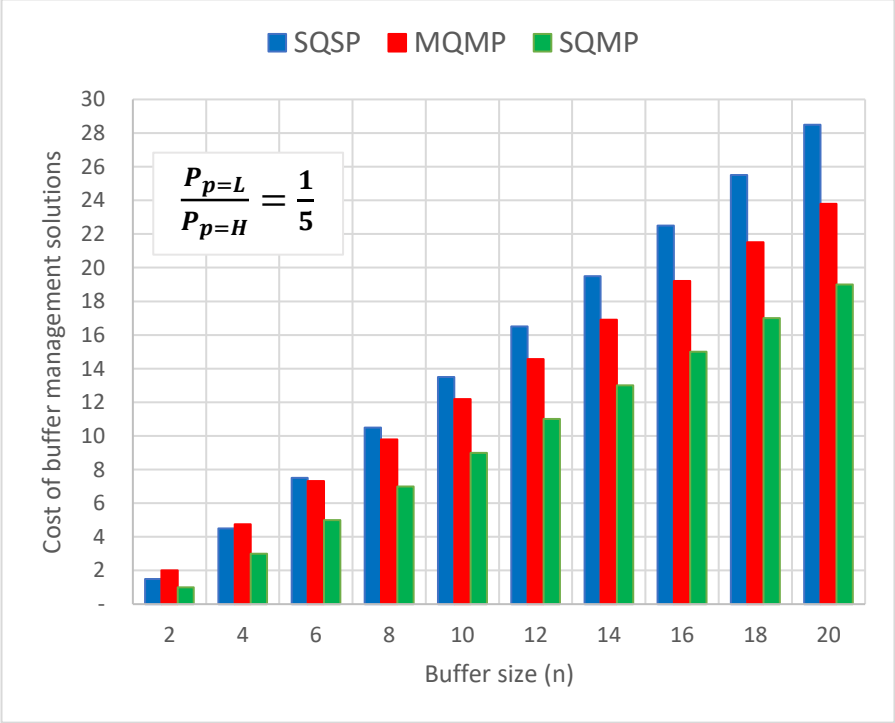


**Figure 3.7** Impact of buffer size on the cost of buffer management (1/5)

Although the success of SQMP in terms of total cost is obvious, there are some important performance metrics that are not taken into account during the mathematical analysis such as fairness. In our analysis, the fairness between different priorities is ignored and thus it should be noted that SQMP could perform poorly in terms of fairness. This is actually a result of the approach that SQMP adopts rather than a structural characteristic of it. However, there is a way to escape from this problem in SQMP. If fairness is desired between different priorities in SQMP, related packets should be assigned to the same priority class. In this way, SQMP will not make any prioritization between packets and will treat all packets the same as in SQSP. Another problem that can be seen in SQMP is finding the exact location of lower priority packets on the buffer and replacing them with higher priority ones. It is true that this process is more complicated than FIFO, and needs more energy and processing time. However, the problems driven by such side effects are quite limited and they can be ignored for the sake of a better performance. Since the buffers used on the sensor nodes are very tiny, it is possible to search and replace packets on the buffer very simply and quickly. It is known that the searching and replacing is a big problem for large arrays but in the sensor nodes the search area is quite limited, so the extra time and energy, used for searching and replacing packets, were ignored in our conceptual model.

# CHAPTER 4

## SIMULATION RESULTS AND DISCUSSION

In this chapter, the general performance of three different buffer management solutions will be examined in different aspects and they will be assessed whether they are appropriate for the WSN environment. As is known, the capacity of memory in sensor nodes is quite limited due to the cost constraints, thus these memories can easily overflow and the congestion can be experienced relatively easily in WSNs. It should be also noted that some characteristic features of WSNs play an active role on such and other similar performance degradations. Actually, all buffer management solutions are suffered from the performance degradation during the transmission of packets on the network and the underlying reasons of these degradations in WSNs are the main subject of this chapter. During the examination of the mentioned reasons, simulations and the comparative analysis of the results taken from various simulation scenarios are going to help us in here.

The results obtained from simulations, performed with different seeds, will be presented in here through comparative graphs. The performance results of our proposed solution that addresses the problems originated from the deficiencies of the well-known buffer management solutions is also presented in here. In order to increase confidence level, each simulation is repeated with different seed values and the average of results obtained from the simulations are used in the graphs. Each graph provides a great deal of information about performed simulations and sheds light into the relations between MAC layer plans and the buffer management solutions employed on this layer. In the following, the results based on different simulation scenarios are discussed in detail and analyzed comparatively. During the comparisons, which are made between different buffer management solutions and their performance results one should be careful to avoid misunderstandings. In order to reveal how buffer management solutions affect the success of a communication layer and the protocol on this layer, the simulations are diversified and enriched.

Before the presentation of simulations and the corresponding results, basic steps of the adopted approach for the simulations and the way of their interpretations should be mentioned. The simulations and their comparative analysis were performed in two-fold: Simple Deployment and Extensive Deployment. More simple simulation scenarios and some additional preparations are needed to fully understand about how MAC layer interact with buffer management solutions before more comprehensive simulations can be undertake. Some simulation parameters are shared between these two different deployment scenarios while some others are not. In the following, the simple deployment and related findings are presented in first and afterwards the extensive deployment is given and discussed.

## 4.1 Simple Deployment and Basic Simulation Setup

Simulation is one of the most preferred methods to compare different approaches proposed for WSNs. We use Omnet++ and Castalia as a simulation platform [64,65] and in our simulation, there are three different types of sensor nodes: source node which is used for generating packets, sink node which is the main target node for transmitted packets, and intermediate node which forwards packets to the sink node after buffering them. The intermediate node option has been left out of the simple deployment because they increase the complexity that can lead inaccurate interpretations of the simulation results.

It is assumed that there are no predefined or static determinations of roles about sensor nodes in our simulations. Any task mentioned above can be performed by all sensor nodes regardless of whether there is a predetermined division of work or role among sensor nodes. For instance, a node that is a source node in a particular case may be an intermediate node in another case. It should be noted that the predefined assignment is valid for only the sink node and it is not changed from the beginning to the end of an application in the simulation. However, the sink can be determined differently at the beginning of simulation for different applications.

There are two physical phenomena in the simulation environment that are monitored around the source nodes and packets generated by these source nodes must belong to one of the two priority classes in accordance with monitored phenomena. However, packets can be also assigned to different priority classes without paying attention that there is a direct relation between the phenomenon and the priority class. In other words, determination of the priority of any packet can be done on a phenomenon basis or it can depend on other different parameters. Thus, it can be said that there are no assumptions for assignment of priorities to packets. The priority of a packet is set in the source node at application layer, but it can be changed while it passes through different lower layers or it can be recalculated during routing on intermediate sensor nodes. A quite important necessity for WSNs is that a priority is able to assigned to a packet dynamically and it can be changed repeatedly by observing the packet importance on the reconstruction process of the sensed information throughout the route path from source node to the sink node. As an example, it is clear that the nodes located around the sink node are able to transmit packets to sink node more easily because of their location advantage. Besides, the probability of experiencing the funnel effect is much higher for farther sensor nodes. A prioritization mechanism, which considers such cases, should be established on the network to balance prioritization in favor of nodes which are located far from the sink node. Although the mechanisms used for prioritization is beyond the scope of this thesis, the buffer management solutions, which are an important component of these mechanisms, are one of the subjects of this study and therefore different buffer management solutions are examined in terms of whether they provide the necessary support to prioritization mechanism that is employed on the network. The success of the overall mechanisms used for prioritization in WSNs is tried to be uncovered through simulations performed with different buffer management solutions.

The format of an application packet used in our simulations is shown in Fig. 4.1. An application packet mainly consists of two parts: header and payload. An application packet starts with 8 bytes of header, followed by 12 bytes of payload, thus each application packet is totally equal to 20 bytes. The header holds the parameters that

will help the decision makers along the route path, while the payload holds the actual data which is used for the construction of the actual sensed information. In view of buffer management solutions there are two important parameters on the header which is represented in our simulation with *pktTimeout* and *pktPriority* fields respectively. An information, which corresponds an event or situation detected by the sensor nodes, is constructed by looking at first these two fields. The *pktTimeout* field determines the deadline of validity of the packet, whereas the *pktPriority* field determines its importance and priority.

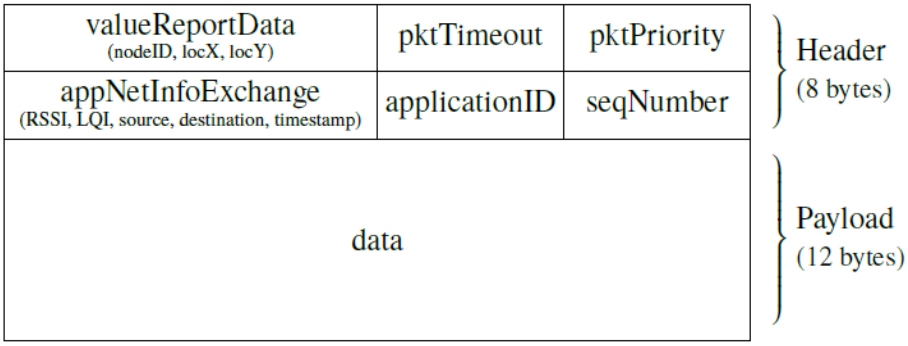


**Figure 4.1** The format of an application packet

Each simulation is repeated with different seed values at minimum 100 times. The simulation results are calculated as the average value of these 100 runs. The reason why simulations are repeated so many times is to increase the confidence as much as possible. The obtained confidence level of the results in the simulations is shown in Fig. 4.2. As can be seen in the given figure, the deviation of the results is approximately 0.5% or below when the confidence level is taken as 95%. This is significant in that it shows that the accuracy of the results obtained from the performed simulations is quite high.

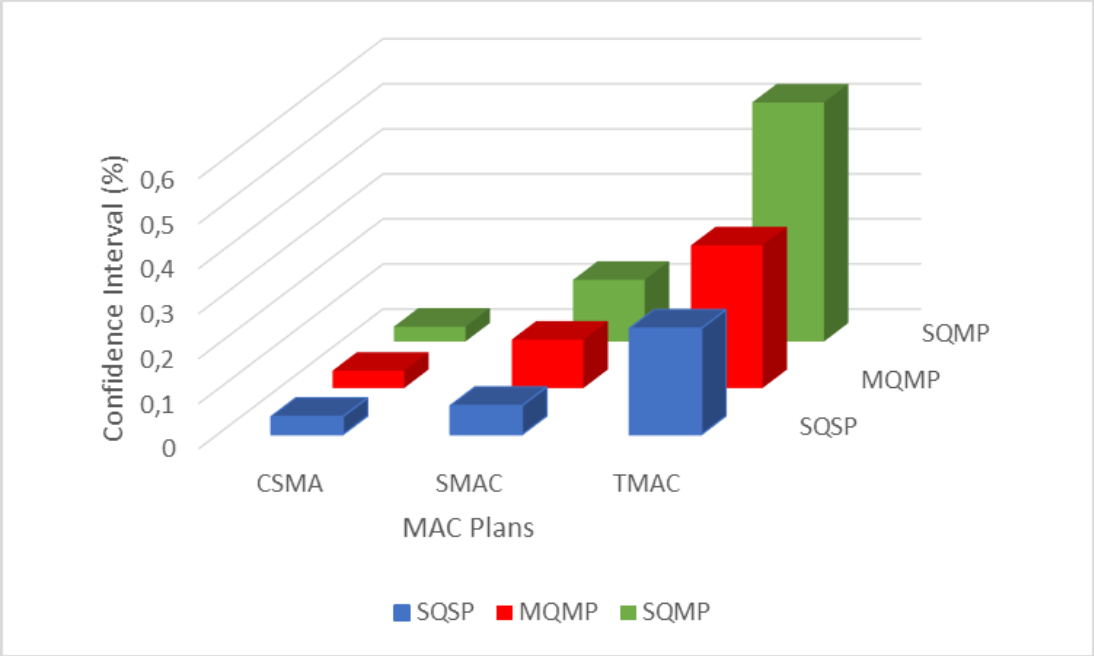


**Figure 4.2** Confidence interval of the simulations

Before proceeding to simulations that will be examined in the following, it is necessary to open an enlightening window in here to interpret these results more properly. Before extensive network simulations, the simulations performed on a simpler and a controlled environment would provide a clearer picture about the reasons that lie behind the behaviors shown by different buffer management solutions. This will also provide us new insights on results obtained from simulations and shed light on possible dark points encountered when we try to explain them. In accordance with this purpose, a simulation environment with a single source and a sink node on a relatively simple and more controlled network have been prepared as in Fig. 4.3. In this simulation environment, all sensor nodes can communicate with each other directly without needing any intermediate or forwarding nodes. In each simulation, the source node generates the same number of application packets and sent them to sink node only. Application packets are exchanged between just these two sensor nodes: the source and the sink, which are marked with 1 and 0 respectively on the related representation given in below. The important simulation parameters used for the simple deployment scenario can be seen on Table 4.1.

**Table 4.1** Simulation parameters of the simple deployment

| **Parameter** | **Value** |
|---|---|
| Total Area | 15m X 15m |
| Number of nodes | 9 |
| Placement of sensor nodes | Grid |
| Number of priorities on the network | 2 (High, Low) |
| Buffer size | 16 |
| Number of sink nodes | 1 |
| Number of source nodes | 1 |
| Sink location | [0,0] |
| Simulation platform | Omnet++ with Castalia |
| Number of simulation runs | 100 |
| Radio | CC2420 |
| Radio range | 30 meters |
| Packet deadline | Infinity (No deadline) |
| Routing protocol | No routing |
| Generation ratio of packet priorities | 1 (High/Low) |

Since the communication range of the sensor nodes is determined to be 30 meters, the sink node (node 0) can communicate directly even with the farthest node (node 8) without need a forwarding node. It means that there is no need a routing protocol for the communication between any two end nodes in this simple network deployment scenario. In this way, the problems arising from the routing protocol and its internal processes could be avoided. Moreover, by limiting the number of main sensor nodes with two and keeping the distance between nodes very limited, it is becoming possible to minimize well-known signal errors such as fading, interference, multipath cancellation etc. Thereby, the interactions between buffer management solutions

employed on the sensor nodes and the MAC layer plans have been come out more fully and clearly, and the unexpected problems that can be encountered during the communication have been prevented as much as possible.

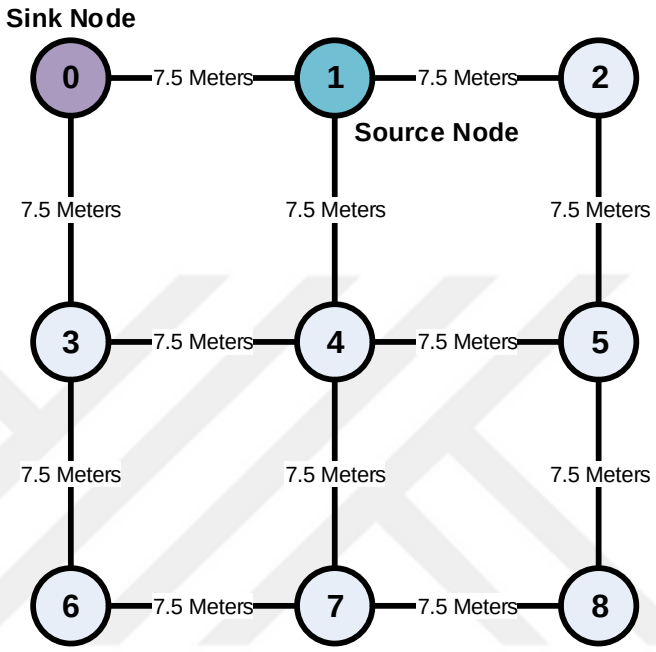


**Figure 4.3** The simple sensor node deployment

In the following, the performance results of SQSP, MQMP and SQMP buffer management solutions will be reviewed and important interactions between them and employed MAC plans are shown with comparative graphs. Here, the total number of sent packets (TX), the number of packets received by the sink node (RX), and the number of data packets received and interpreted successfully at the sink node (DX) will be presented under each graph. The duration of the simulation and the number of packets generated by the source node have been kept same for all simulations in the simple deployment scenario.

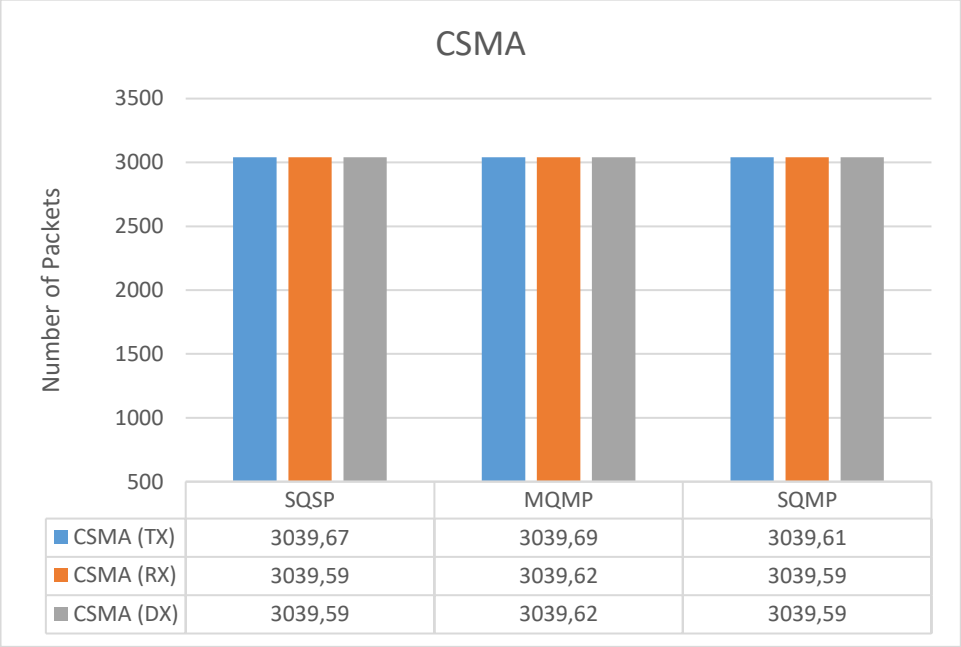


**Figure 4.4** TX, RX, and DX packets in simple deployment for CSMA

The first graph is about the CSMA MAC plan and it is given with Fig. 4.4. This figure graphically shows that the TX, RX, and DX results obtained from the simulations in case the CSMA MAC plan is employed on the sensor nodes. As can be seen on the graph, all buffer management solutions have produce very close results for this MAC plan. Since the CSMA is a sleepless MAC plan and the main sensor nodes are positioned within communication range of each other, the results obtained from the simulations are very close. This means that there is no noticeable packet loss or drop experienced on the sensor nodes due to the employed buffer management solutions. In other words, it is possible to infer that the buffer management solutions used for the CSMA MAC plan have very little effect on the number of application packets that are aggregated successfully on the sink node. This is of course valid for only point-to-point communications in WSNs.

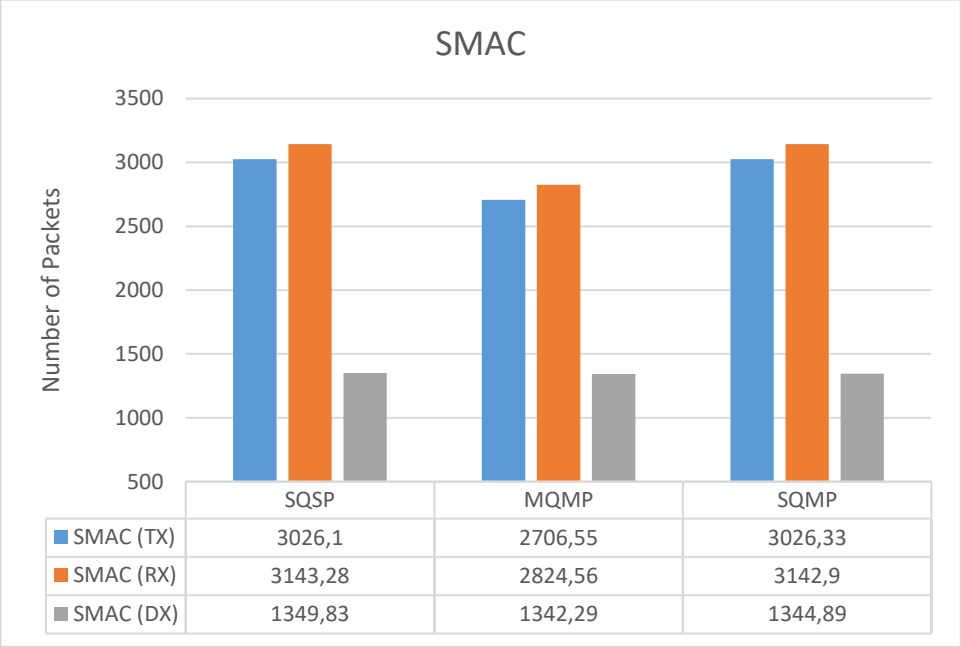


**Figure 4.5** TX, RX, and DX packets in simple deployment for SMAC

The second graph could be seen in Fig. 4.5 and it shows the relationship between the total number of sent packets (TX), the number of packets (RX) received by the sink node, and the number of data packets (DX) aggregated successfully on the sink node for the SMAC, which is one of the most important medium access protocol for WSNs. In this figure, it is observed for MQMP a striking decline on the number of packets sent to and received by the sink node. This is due to the wasteful nature of the MQMP in terms of buffer utilization and this feature seems to be influential both on the number of packets sent and received. On the other hand, for all buffer management solutions, the number of data packets aggregated successfully on the sink node is very close to each other, and the impact of inefficient buffer utilization of MQMP is less felt on the transmission of actual data packets. This provides a relatively more acceptable level of performance for MQMP solution. The lack of priority assignment or a lower priority assignment for packets used by MAC layer such as synchronization packets have functioned as a leverage for the transmission of actual data packets. This means that in a buffer management solution that can differentiate packets and use prioritization among them, the packet losses are shifted to the lower priority packets as in seen in

the SMAC. This is the reason why the number of data packets aggregated successfully on the sink node in MQMP solution is in close proximity to other buffer management solutions for the SMAC MAC plan.

Having a careful look on the data presented in the Fig. 4.5, there is an interesting point that the number of data packets aggregated on the sink node is at a fairly low level if it is compared to sent or received packets regardless of which buffer management solution is in use. This means that some of the data packets which are sent to the sink node could not reach that node in some way. In order to better understand the underlying reason of this, one can look at Fig. 4.6 which shows how packets sent to the sink node were processed in general. With the help of this figure, we have actually reached an important insight into the nature of SMAC protocol. Since the duty cycle periods in the SMAC protocol are static and cannot be extended, packets are lost at receiving side because the radio is turned off at receiving node without regarding whether there are more packets to be wait for sending. This explanation appears consistent with the results in the figure: The significant portion of the packet losses experienced in the SMAC protocol is due to the fact that the radio is not ready (RX state) to receive the sent packets. As a result of this, packets located at the back of the buffer in the SMAC are unintentionally lost. However, the impacts of this unintentional losses on actual data packets seems to be very limited for MQMP because it affects only low priority packets which includes non-data packets such as sync packets.

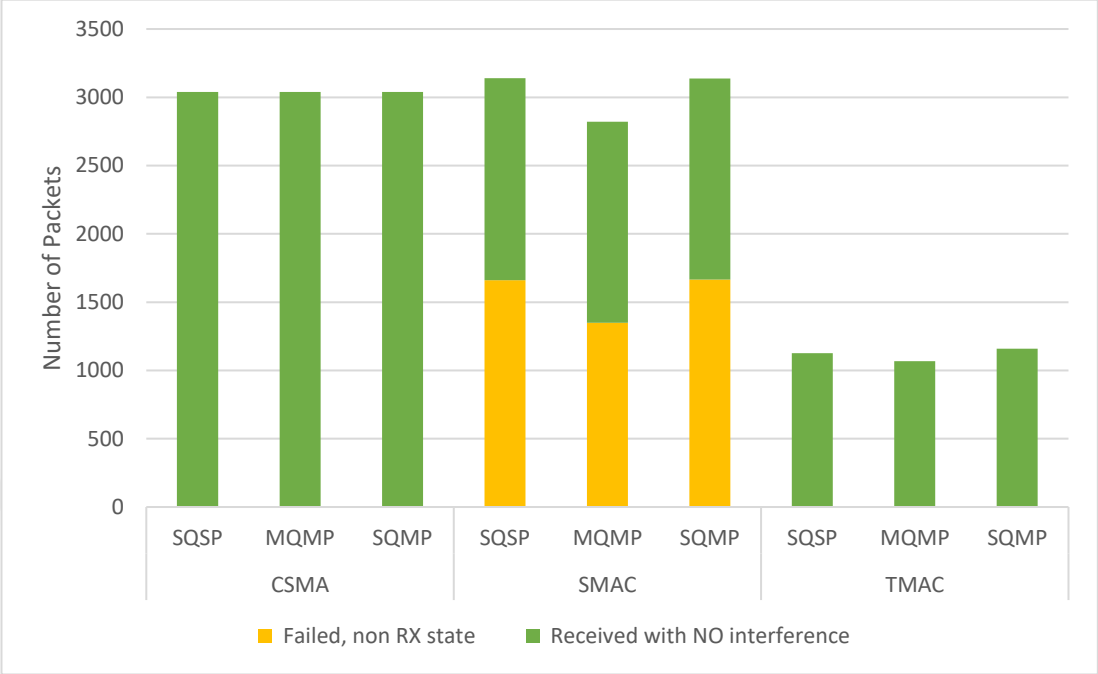


**Figure 4.6** The final state of the sent packets

Another interesting fact shown in Fig. 4.5 is the difference between sent packets (TX) and received packets (RX). As it can be seen clearly in the figure, the number of packets which are sent to the sink node is less than the number of packets received by that sink node. In other words, there is a strange case in which there are more received packets at sink node than packets sent to it. However, there is an important point to be noted here; in such a way that all nodes in the network constantly send and receive packets to/from each other in order to ensure local connectivity and the nodes within the same radio range can overhear these packets. This strange case is due to the packets that do not actually target the sink node but are overheard by the sink node. Although these packets are sensed at the sink node, they are ignored and not processed further. For this reason, the number of packets received by a node in WSN may be greater than the number of packets sent intentionally to that node. This is a fairly common occurrence that is encountered in many MAC protocols, including those particularly developed for WSNs. It is quite clear that this should be carefully addressed in the buffer management solutions proposed for WSNs and the required countermeasures

should be taken on the buffer management mechanism to prevent such similar side effects that affect the utilization of buffer easily.

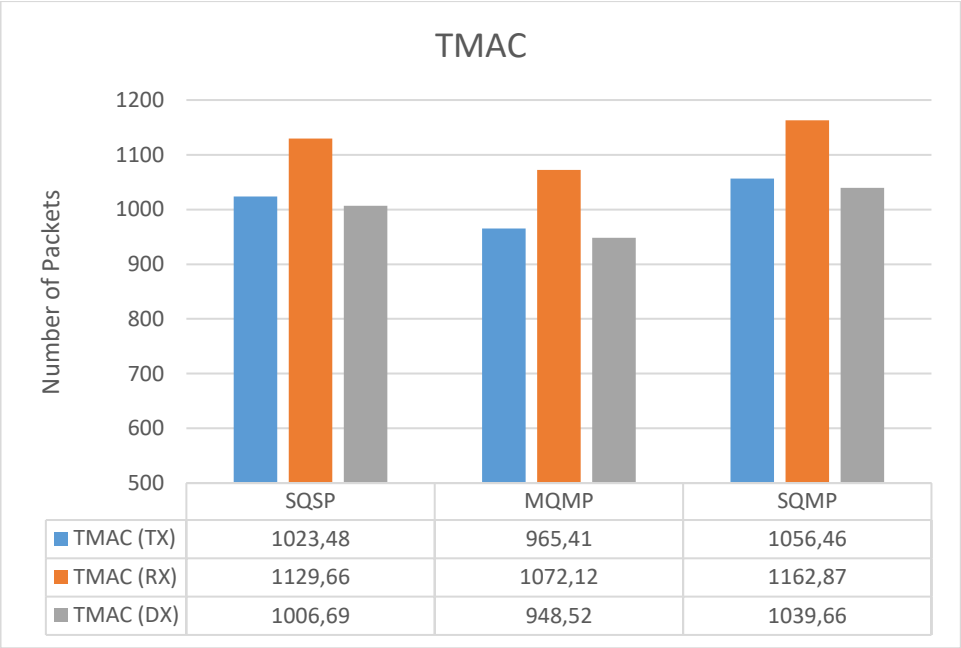


**Figure 4.7** TX, RX, and DX packets in simple deployment for TMAC

The results obtained when similar simulations are performed with TMAC MAC plan are presented in the Fig. 4.7. According to the figure, the number of packets received by the sink node in TMAC is more than the number of packets targeted to the sink node as in SMAC given with Fig. 4.5. However, compared to SMAC, it is clearly seen that TMAC was made proportionally more non-data packet exchanges. The underlying reason of this fact is that TMAC is a more adaptive MAC layer protocol. Since TMAC based sensor nodes can extend their duty cycles according to communication needs, they send and receive more sync packets or other similar MAC layer packets to inform all other nodes about such changes. In conclusion, TMAC, as an improved version of SMAC protocol, has a relatively higher packet exchange intensity for non-data packets. It also means that the growth seen on the number of packet exchanges leads an additional stress on the buffer management solutions employed on sensor nodes in a certain way.

Another difference between SMAC and TMAC is the dissimilarity which is observed between the number of packets (TX) which is sent particularly to the sink node and the number of actual data packets (DX) that is aggregated successfully on the sink node. Contrary to SMAC, it is seen that the packets sent in particular to the sink node was successfully received by the sink node in TMAC plan at a very high rate and unexpected packet losses is minimized eventually. In accordance with this observation, if taking a careful look at Fig. 4.6, it can be easily seen that the packet losses in TMAC due to the turned off radios are too low in comparison with SMAC. As a result, it can be said that the amount of energy consumed for the transmission of each packet in the TMAC is less than for the SMAC.

Regarding the performance results presented by different buffer management solutions in TMAC, it is apparent that the best results belong to the SQMP whereas the worst results belong to the MQMP buffer management solution. If the results are examined more closely, it is clearly seen that the low-level utilization of buffer in the MQMP solution seems to be caused a noticeable decrease on the number of data packets aggregated successfully on the sink node. This is, in fact, not compatible with the expectations. While the expectation is that the performance of MQMP is much better than the SQSP, the results obtained from the simulations are different far from the expectations. However, MQMP still show better performance in comparison with SQSP in terms of total cost because MQMP is able to provide necessary prioritization among different packet flows. This can be also seen at Fig. 4.8 which is shown in below. As can be clearly seen in the figure, there is no important difference between results obtained from different buffer management solutions in the case of CSMA, which is known as a sleepless MAC plan. However, in the case of SMAC and TMAC plans, a significant differentiation is observed in high priority packets aggregated on the sink node. Although the performance results of the MQMP is better than the SQSP in terms of total cost, but in the case of the SQMP, MQMP still has worse results. According to results shown in the Fig. 4.8, the SQMP outperforms the other two buffer management solutions in terms of the prioritization of high priority packets.

Another interesting result observed in TMAC is that SQSP and MQMP solutions gives very similar results for this MAC plan, similar to the CSMA plan. Underlying reason of this is the fragmentation of memory and the wastefulness that is caused by the prioritization mechanism used by the MQMP buffer management solution. In addition, dynamic and relatively long sleep durations of TMAC further increases the level of scarcity which is already exposed by MQMP. As a result, the performance of the MQMP buffer management solution is severely degraded in TMAC, which is another one of the most important MAC layer plan for WSNs.

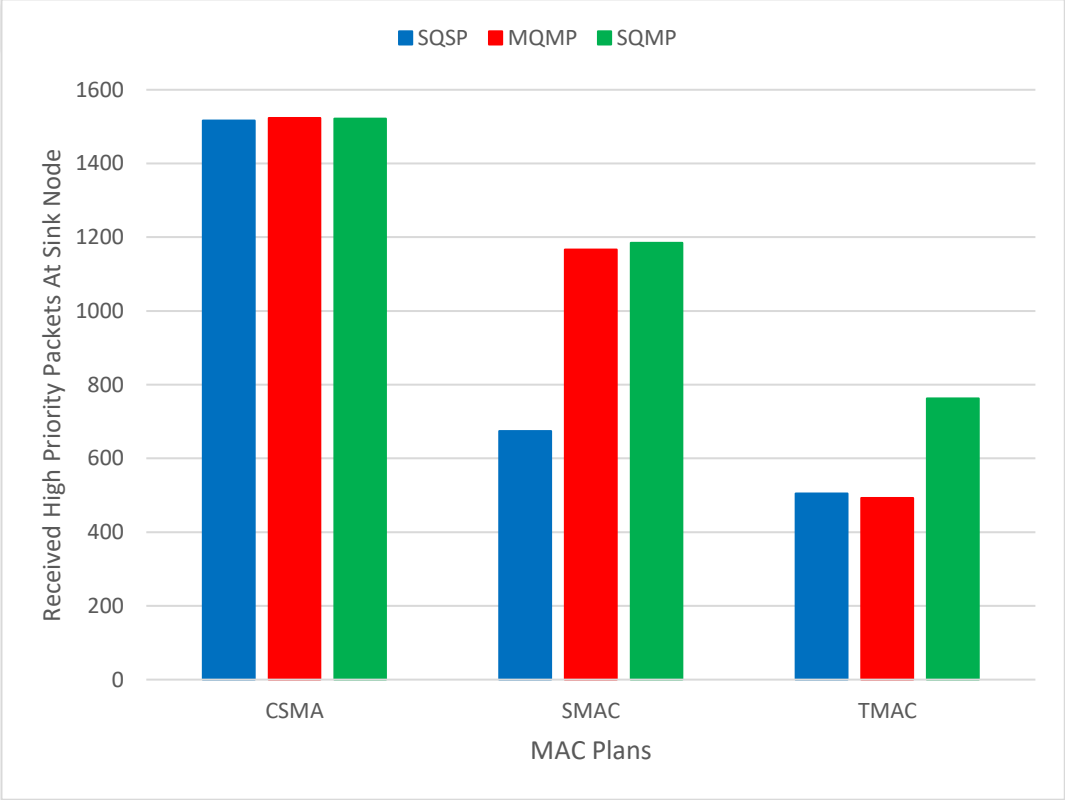


**Figure 4.8** The number of high priority packets aggregated on the sink node

An assessment of the potential impact of basic buffer management approaches on MAC layer performance bring us to an important point and force us to make also an important decision. The buffer management solution to be used on sensor nodes in WSNs needs to be determined before the deployment of the sensor nodes. On the other hand, it is shown that the well-known buffer management solutions, which are

examined and discussed above, cannot adequately meet the requirements of WSNs. Alternatively, the new buffer management solution SQMP developed and examined in context with this study provides a greater efficiency and effectiveness to WSN researchers. The improvements proposed by the SQMP solution seems to achieve more successful results than the results achieved by other two solutions. This success can be also clearly seen in the comparative graphs presented in above.

MQMP, the defacto solution adopted and used in many WSN researches to gain prioritization capabilities which is not originally available in SQSP buffer management solution, could not provide expected results due to wasteful nature of MQMP, which is sometimes called as memory fragmentation in here. It seems that the MQMP is aiming at effective memory use, but it has to somehow compromise the efficiency in memory management. For the sake of overcoming such difficulties that encountered in WSNs, it is proposed by the author of this study the SQMP solution in which both features are trying to be supplied without sacrificing one another.

## 4.2 Extensive Simulation Results and Discussion

The main difference between the simple and the extensive deployment is the approach that is used for modelling and explaining the real world implementations of simulations, and the level of complexity followed therein. There are three main traffic patterns simulated on the network, which is not present in the simple deployment. The performance of the buffer management solutions have been re-examined under new circumstances based on a much broader scale in this new simulation setup. The traffic patterns are designed to simulate Uncongested, Congested and Very Congested network conditions. With the help of these traffic conditions, the success of each buffer management solution can be evaluated under new conditions and the utilization level of buffer on the sensor nodes can be explored at network level. This work, which can be seen as a kind of stress test, will attempt to show how well handle the congestions which can be experienced in real world WSNs more easily. The present simulations have focused on behaviors of different buffer management solutions in extended simulation scenarios.

**Table 4.2** Simulation parameters of the extensive deployment

| **Parameter** | **Value** |
|---|---|
| Total Area | 100m X 100m |
| Number of nodes | 50 |
| Placement of sensor nodes | Uniform |
| Number of priorities on the network | 2 (High, Low) |
| Buffer size | 16 |
| Number of sink nodes | 1 |
| Number of source nodes | 3 |
| Offered load | 3.2 pps (Uncongested)<br>32 pps (Congested)<br>320 pps (Very Congested) |
| Sink location | [0,0] |
| Simulation platform | Omnet++ with Castalia |
| Simulation Time | 100 sec |
| Number of simulation runs | 100 |
| Radio | CC2420 |
| Radio range | 30 meters |
| Packet deadline | 20 Sec |
| Routing protocol | Multipath Ring |
| Generation ratio of packet priorities | 1 (High/Low) |

In extensive simulation setup, we have used a different method for the placement of sensor nodes and the number of nodes in the network is increased in comparison to the simple deployment. It is attempted to present a projection of the real world WSN implementations in the new deployment and simulation setup as much as possible. In this context, intermediate nodes have been included as an important active component

in this new deployment plan and a routing protocol has been configured on the sensor nodes to forward packets end-to-end fashion. The simulation parameters of the extensive deployment and the other details can be seen on Table 4.2.

Some features and simulation parameters differ from simple deployment for extensive deployment, whereas some features and parameters are valid for both deployment scenarios. As shown in Table 4.1 and Table 4.2, the simulations are repeated at least 100 times not only for simple deployment for also extensive deployment to increase the confidence level of the simulation results. The average of the results obtained from these simulations are presented through comparative graphs in the following.

The first graph is about the packet transmission rate of the buffer management solutions under different traffic conditions and the energy consumed in average during the simulations. The energy consumption per node and the total number of packets aggregated on the sink node can be seen in the Fig. 4.9. This figure shows that the CSMA, which is a sleepless MAC plan, has the highest packet transmission rate as expected. On the other hand, the lowest packet transmission rate belongs to the SMAC both for congested and very congested traffic conditions. The underlying reason of this is one of the working principles of SMAC plan. In SMAC, sensor nodes have static duty cycles, and therefore packets at the back of the buffer may not be properly transmitted to next hop during congestion. Packets are lost because the receiving node goes to sleep when duty cycle reaches the timeout in the middle of the packet transmission and the sender node is not informed about this state transition.

In the same figure, the little rise, seen on the TMAC plan for congested and very congested network conditions, is originated from the dynamic duty cycle principle of the TMAC plan. Unlike the SMAC's static duty cycles, sensor nodes can dynamically schedule their duty cycles in line with their needs in TMAC. This means that if a node is required to transmit more packets, the duty cycle of the sensor nodes can be extended in TMAC and thereby the packet loss experienced on the sensor nodes can be reduced. An interesting result claimed also in this study is that MQMP based buffer

management solutions provide a lower buffer utilization in comparison with single queued buffer management solutions.

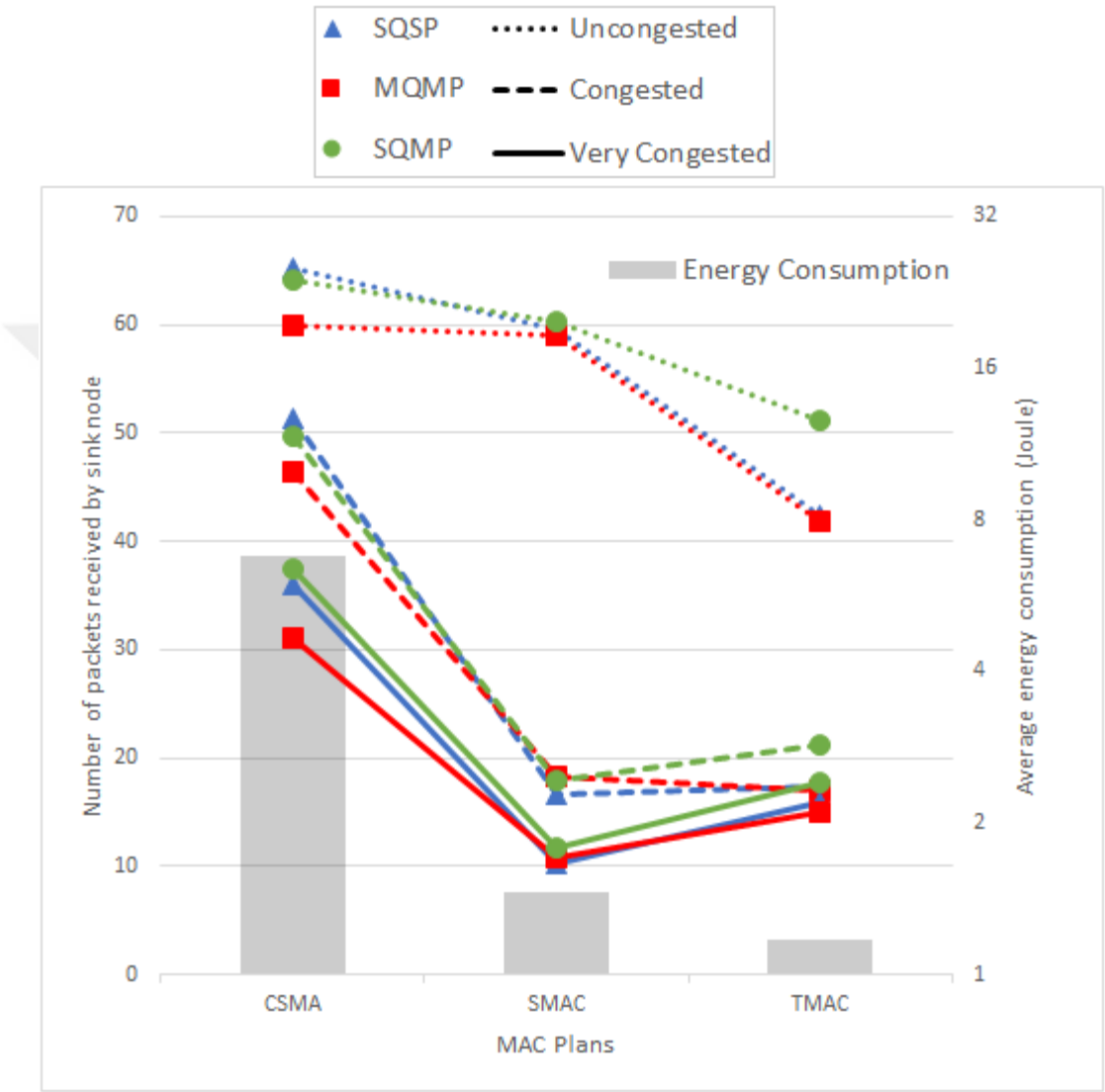


**Figure 4.9** Packet transmission rate and energy consumption

In the case of a comparison among MAC plans in terms of energy consumption, it can be seen that the most energy is consumed by the CSMA and the least energy is consumed by the TMAC. Although this is highly predictable, these results also lead us some unforeseen new interpretations. As an example, in particular under congested and very congested traffic conditions, it is seen that the SMAC shows a lower

performance than the performance achieved in the TMAC plan. Though SMAC is expected to show better performance because of its high level of energy consumption, it is seen that completely different results have taken from the simulations. The most important factor underlying this problem is the fact that the mechanisms employed by different communication layers are not completely independent of each other in WSNs and the layers' can adversely affect each other's performance due to vulnerable and intertwined features of sensor nodes. Within this work, it was shown that a MAC plan in which a higher performance with a lower energy consumption can be achieved. The cooperation between MAC layer and the buffer management solution employed on can provide necessary prioritization between packets without affecting the total buffer utilization, and improve the general performance of MAC layer solution.

Another important result taken from the simulation is given in Fig. 4.10 in which the number of loss packets is shown. Again in this figure, it is clearly seen that the most packet loss is experienced in MQMP based buffer management solutions. On the other hand, the best results are belong to the SQMP. Although there are many approaches proposed to avoid packet losses or to recover lost packets during transmission, no mechanism has been used to reduce packet losses in our simulations. As a result, the packet losses shown in the simulation results are relatively high. Nevertheless, this does not change the success of SQMP among different buffer management solutions in terms of packet loss. According to this figure, it is witnessed that the SQMP shows a better performance, in contrary to MQMP buffer management solution, which is commonly accepted and used in many WSN implementations in order to differentiate and prioritize packets in accordance with their priority classes.

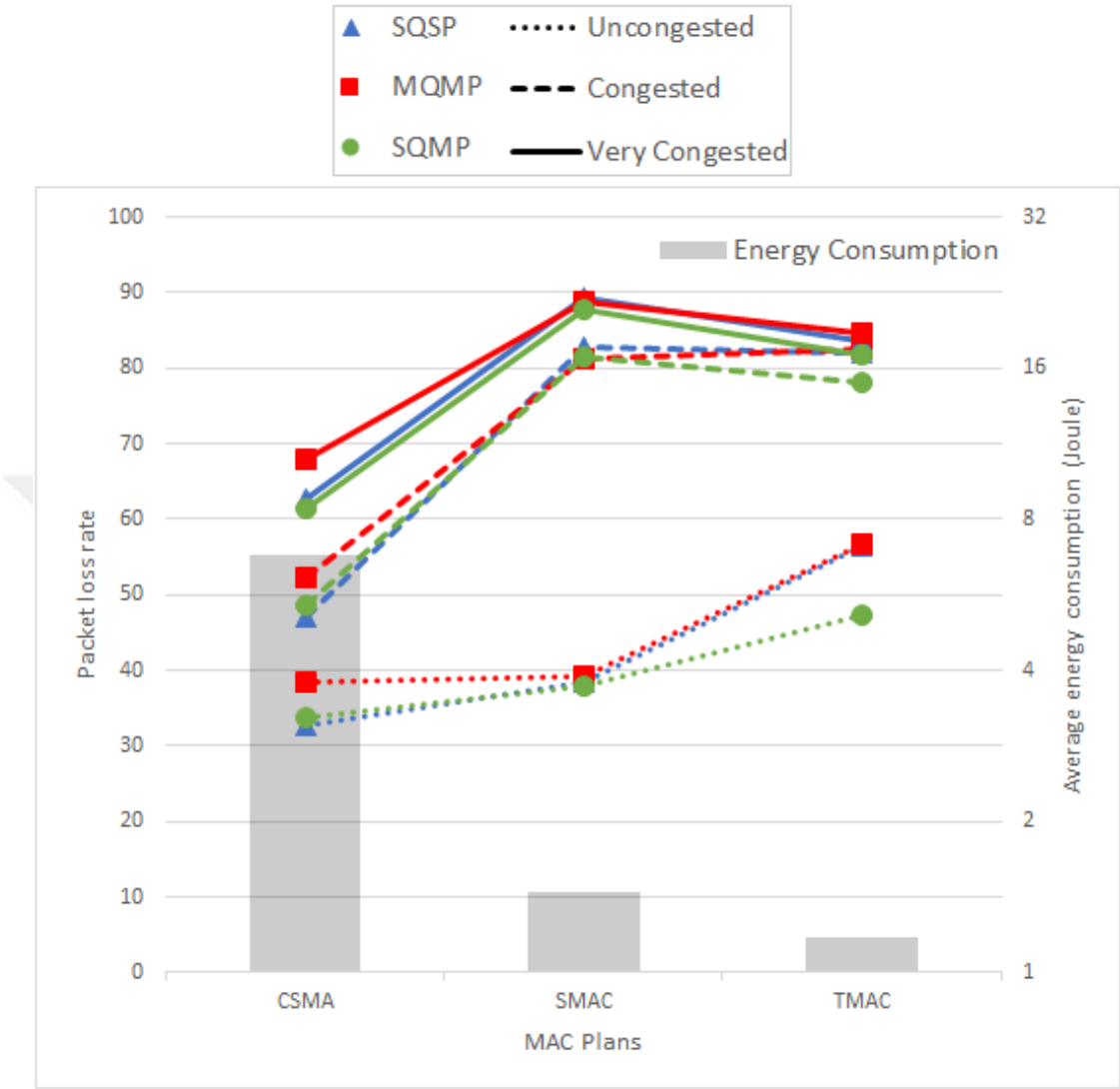


**Figure 4.10** Packet loss rate and energy consumption

High priority packets are more important packets in the network and they should be reported to sink node more effectively. In Fig. 4.11, high priority packet transmission performance of different buffer management solutions and changes in performance under different traffic conditions are shown. TMAC is the MAC plan with the least energy expenditure among the simulated MAC plans and SQMP shows the best performance for TMAC plan without regarding which traffic pattern (Uncongested, Congested or Very Congested) is in use. According to the figure, the high priority packet transmission performance of all buffer management solutions degrades with

congestion, but SQMP controls this degradation more effectively compared to other two solutions. Since buffer capacities on the sensor nodes are sufficient for forwarding packets under uncongested network environment in general, the number of high priority packets aggregated on the sink node is very close for CSMA and SMAC plans. However, the performance improvement provided by SQMP on TMAC plan is quite obvious. As a result, it is clear that the SQMP has much better performance from the point of prioritization of high priority packets according to these simulation results.

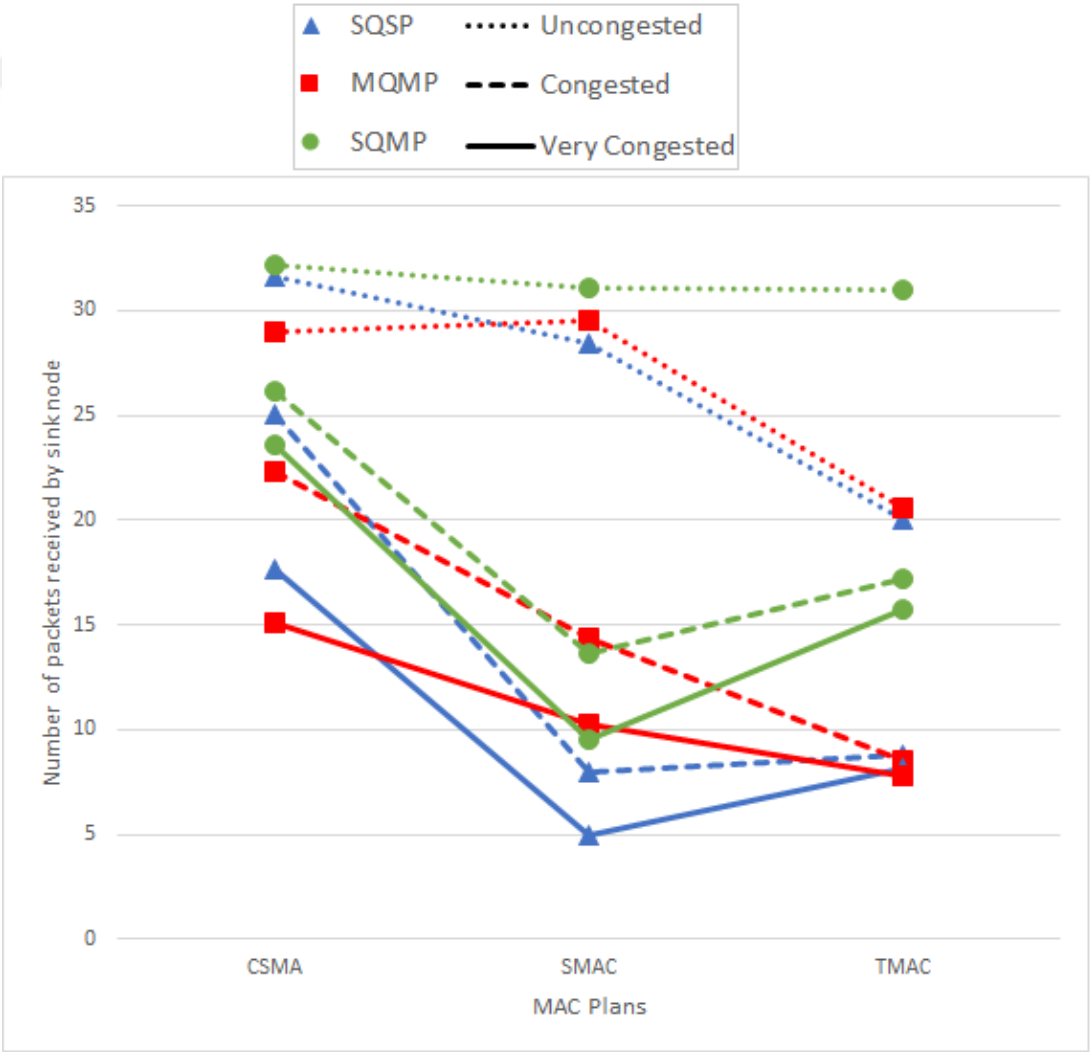


**Figure 4.11** High priority packet transmission rate

In the case of injecting a new high priority packet into the network, called it as "critical packet", the performance results obtained from the simulations are given in Fig. 4.12. In this figure, buffer management solutions are compared according to their handling capabilities in case of there is a packet in the network, which is not belong to a known priority classes. During simulations, such a critical packet was generated on each source node and sent to the sink. According to the results, SQMP shows, without doubt, the best performance among examined buffer management solutions. The ability of SQMP to provide prioritization between packets without using predefined priority queues is the most important underlying reason of this result.

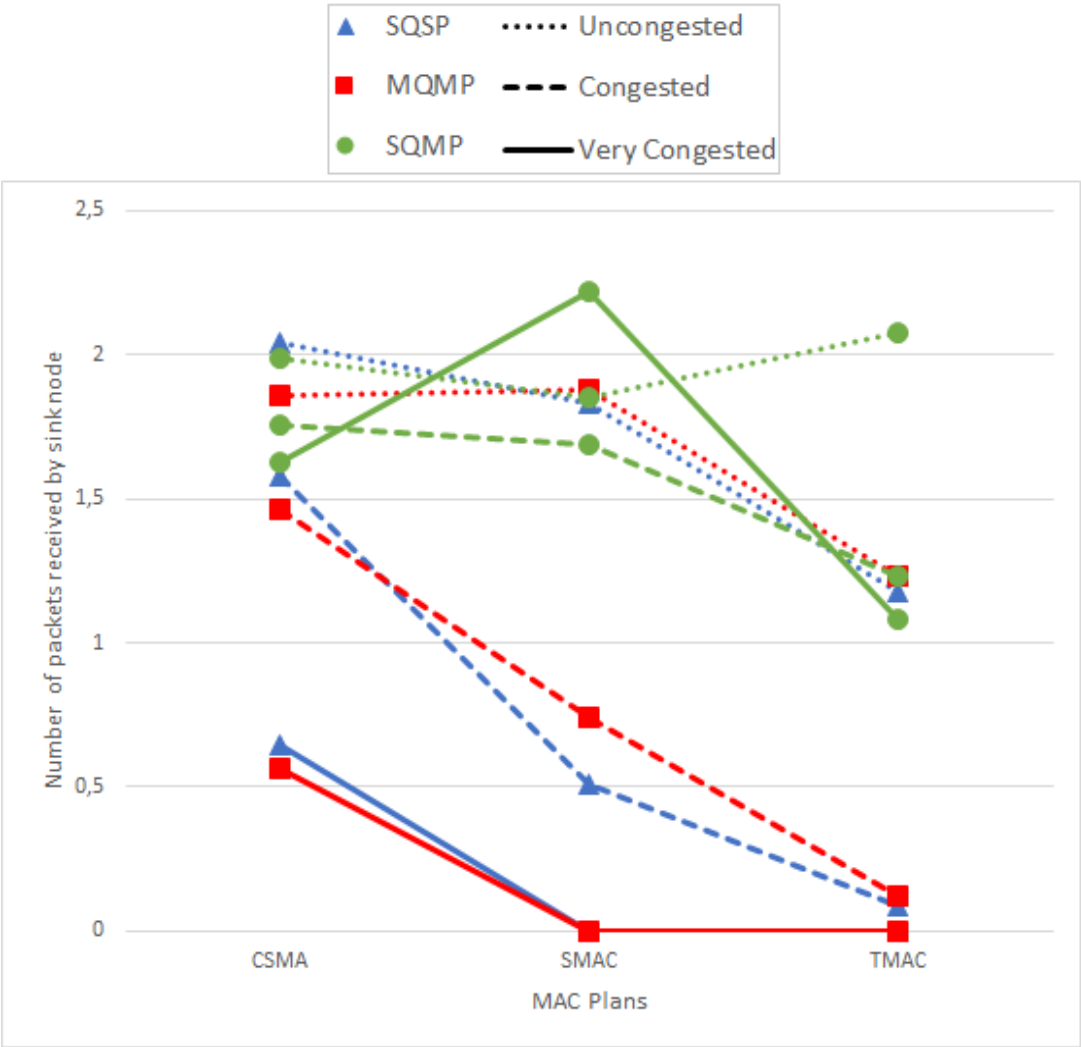


**Figure 4.12** Critical packet transmission rate

According to results obtained from both simple and extensive deployment simulation scenarios, it is clearly seen that SQMP is the best solution for WSN environment among examined buffer management solutions. The MQMP expects some structural pre-determinations such as number of queues on the sensor nodes, priorities of packets and their operational steps, whereas there is not such requirements for SQMP based WSNs. In addition, SQMP mitigates an important burden by transferring the prioritization to a network-wide mechanism, which is responsible in entire network for the prioritization of packets and the determination of its relevant steps. Thanks to this delegation of authority and responsibility, the prioritization mechanism current in entire network has been contributed to become more robust and consistent.

High priority packets can be generated based on a specific sensor on the node or an application in the network. Furthermore, the priorities assigned somehow previously can be changed by intermediate nodes later during the routing of packets. According to employed network-wide prioritization mechanism, the priority of any packet can be changed continually and a new priority can be assigned to the packet at any point in the network until it is delivered to the final destination that is the sink node. Each application and each sensor node may be allowed to decide whether a packet has higher priority. However, all these changes are made by the network-wide prioritization mechanism according to necessities of the network. Our solution, only checks the bits on the header to judge which packet has higher priority and accommodates incoming packets to appropriate position on the buffer. The representation of high priority packets with some additional bits on the header of packet, which is adopted in our simulations as well, could be also made with different methods in different WSN implementations. However, thanks to this feature, the SQMP allows for a more flexible prioritization mechanism in entire network and does so without sacrificing any space of memory on the sensor nodes. This feature is one of the most powerful side of our solution, which aims to improve the buffer management performance in WSNs.

As the simulation results confirm, the SQMP has the ability to differentiate and prioritize different priority classes that are not actually defined in the network. With this novel feature, any priority class can be defined on the network after the deployment of sensor nodes or an existing priority class in the network can be removed in SQMP-based WSNs. This feature provides an incredible capability to applications that are used in WSNs where packets are sometimes marked as critical but this is experienced quite rare. In a mission critical application where the prioritization between packets is supplied with MQMP-based solutions, one or more priority queues, that is empty most of the time, have been re-enabled by the SQMP solution for the packets in different priorities. The differentiation and prioritization of packets in WSNs is currently provided mostly through MQMP-based buffer management solutions, this leads to inefficient use of memory not only in the MAC layer but also in other layers of the communication stack. At this point, SQMP offers an alternative and powerful solution to address such problems that affects also other communication layers other than the MAC layer in WSNs.

# CHAPTER 5

## CONCLUSIONS

This last chapter begins with a brief overview of the present study. After the presentation of the summary of work done, the contributions of the research to the development of knowledge of WSNs have been re-expressed in a simple and clear way. The main limitations of the research area and a few suggestions related to alleviate the side effects of these limitations are presented for the reader's consideration and discussed in detail further in this chapter. Finally, some thoughts about the salient points that researchers and practitioners need to be minded and advices for further works that can be conducted in the future to enhance the approach presented in this study are given.

### 5.1 Summary of Work Done

In this thesis, buffer management solutions have been examined in different aspects and a study has been conducted on how buffer management solutions employed by MAC layer affect the general performance of both point-to-point and end-to-end communication in WSNs. Since the MAC layer is crucial for both point-to-point and end-to-end communication in WSNs, it is focused on the MAC layer in order to better expose the impacts of buffer management solutions on the communication performance in this work. As buffer management plays an important role in ensuring desired and expected QoS at both network and sensor node level, the attention of researchers is shifting to buffer management solutions. Though well-known buffer management solutions could find an application area in various WSN implementations, this approach is actually problematic, and one of the issues that has been emphasized during this study is that the current capabilities and necessities of such a new category of networking as WSN are mostly overlooked by many researchers. The findings presented in this thesis reveal the fact that WSN-specific issues should be addressed with a more comprehensive viewpoint. One of the most

important motivations of the author of this study is that WSNs not only have different constraints but also have various flexibilities and capabilities that are not offered by traditional wired or wireless networks.

According to the extensive literature survey presented in Chapter 2, it is clearly seen that a quite number of solutions proposed for WSNs disregard buffer capacity and energy limitations or duty-cycle and FIFO based problems in WSNs. The fact that the solutions used in traditional networks are desired to be applied directly in WSNs by the researchers seems to be the most important reason underlying this troubled situation. Applying conventional methods on memory without regarding the limitations on sensor nodes results in either ineffective or inefficient use of memory. On the other hand, the buffer management solution proposed in this work provides an optimal solution for buffer management in WSNs and offers novel features. The most important feature of the proposed solution is to make it possible to maximize the utilization of buffer and to prioritize packets between different flows at the same time. Moreover, the ability to prioritize packets that are in a non-predefined priority class could be said to be the most unusual and novel feature of this new solution. In particular, for heterogeneous networks this feature takes our solution one step ahead from others because in these networks sensor nodes are not uniform which means that there could be different buffers and different buffer management plans, and also different packet types and traffic flows.

Another issue addressed in this study is the development of a conceptual model and an analysis approach that allows the buffer management solutions to be compared before they are implemented. With the help of this conceptual model and the mathematical analysis presented within this work, the expected cost values of different buffer management solutions can be quickly established and easily compared with each other. It is considered that the optimum buffer management solution (OBMS) method, which is used as a reference model during the mathematical analysis, can be used for other buffer management solution analyzes to be performed in the future. For this purpose, a comprehensive information on how to use the OBMS and the important points that

should be remembered is presented during our analysis. In addition, the accuracy of the conclusions obtained from the conceptual model and the analyses was confirmed by different simulations performed on the Omnet ++ and Castalia platforms [66], which have a great acceptance in the literature for WSN simulations. In order to increase the confidence level of the results in the simulations, each simulation was repeated at least 100 times with different seed values and the obtained results were presented by means of different comparative graphs to the readers.

Problems originated from the lack of compliance between MAC layer plans and buffer management solutions, and also other underestimations which hinder buffer management solutions from working properly with other layers are among the topics studied in this thesis. It is known that in many MAC plans that have been developed and proposed for WSNs, there are mechanisms which recommend to use duty cycling to save more energy on the sensor nodes. This technique aims to reduce unnecessary energy consumption by sleeping nodes in accordance with a certain plan. However, this technique leads to an increase in unexpected packet losses due to the faster exhaustion of free memory on the sensor nodes. The sensor nodes, which are in sleep mode, are not ready to send or receive packets. Since sensor nodes have to wait longer before they communicate each other, an extra burden on memory is emerged. This is due to the fact that the memory capacity of the sensor nodes is very limited and the traffic generated on the source nodes is bursty, especially in event-based applications. Because of the phenomenon known as the funnel effect in WSNs, the problem originated from the lack of enough free space on memory is getting much more worse towards to the sink node. Moreover, this problem becomes even more chronic in networks consisting of nodes where the memory is fragmented in order to be able to differentiate and prioritize different traffic classes. Hence, it can be asserted that the multi-queued approaches invite this problem more eagerly.

To sum up, we investigated three different buffer management solutions using mathematical analyses and simulations in this work. We examined the effect of different buffer management solutions on the MAC layer performance under different

traffic conditions through simulations. The side effects of different node sleeping techniques, frequently used by MAC layer plans in order to save energy, on the packet transmission rate were also examined in here. According to the simulation results, traditional buffer management solutions either result in low utilization of buffer or lack prioritization of packets. The main contribution of this study is to show the impacts of different buffer management solutions on the performance of MAC layer and to introduce a new buffer management solution called SQMP, which does not require a predefined prioritization mechanism on the sensor nodes. Thanks to this feature, a new priority class could be added to or removed from the network without any additional effort in SQMP based WSNs. The use of full buffer space without fragmentation makes the proposed solution more robust for congestion based problems. Moreover, the prioritization capability of SQMP allows for QoS provisioning in the network. Due to the strict limitations on buffers in sensor nodes, a degradation on the packet transmission rate could be experienced in congested network conditions and the characteristic features of WSNs make this degradation even worse. Especially in bursty conditions, SQMP controls and manages this degradation more effectively in comparison with other two examined buffer management solutions which are SQSP and MQMP.

## 5.2 Research Contribution

The current study aims to provide a conscious among WSN researchers about the issues caused by buffer management solutions employed on different layers of communication in WSNs. For this purpose, a mathematical analysis of well-known buffer management solutions has been presented in this study and then a detailed critique of the existing approaches in the literature proposed for buffer management has given. Afterwards, a more comprehensive buffer management solution in which WSN-based constraints are carefully handled has been proposed. The superior features of the proposed solution have been explored through various simulations, and compared with other existing buffer management solutions. The findings obtained by mathematical analyses were confirmed again with simulations which were run by

using different input parameters and it was seen that the proposed solution reaches more successful results in terms of buffer utilization and the prioritization of packets. During simulations, the problems that are caused by different MAC plans employed by the sensor nodes and different traffic patterns in the network have been investigated and the underlying reasons of these problems have been explored through different simulation scenarios.

Some of the primary outcomes of this study can be listed as the following: (i) it is showed that one of the most important reasons for unintended packet losses at node level is buffer and employed buffer management solutions, (ii) it is showed that existing buffer management solutions ignore WSN-based limitations and lead to inefficient or ineffective use of memory on the sensor nodes, (iii) a conceptual model and related mathematical analysis approach is developed to measure/evaluate and compare the success of buffer management solutions, (iv) a novel buffer management solution that takes into account the needs and constraints of WSNs is introduced and the success of the new approach is showed through comparing it with well-known buffer management solutions, (v) mathematical results are confirmed with simulations which are performed repeatedly with different input parameters and seed values.

The approach proposed in this work is also addressing the communication issues in WSNs originated from the units which are not directly involved in the communication. Such issues, which can be seen as a side effect of other mechanisms and algorithms employed on the sensor nodes, require a more comprehensive viewpoint. In particular, since self-organizing and self-managing network is a highly dynamic system, a small ignorance or a slight inattention in an approach proposed for WSNs can demolish all the expectations in the network and may lead to many odd problems.

It is considered that the buffer management solution developed and proposed in this work will have a significant role in optimizing performance not only at the MAC layer but also at other layers of communication. The buffer is used as a temporary storage area for packets in different types, which are transferred between different communication layers on sensor nodes during sending and receiving data. The

fragmentation of buffer, which is used for prioritization of packets in traditional networks, causes the sensor node to become more precarious due to the inefficient use of the limited capacity and it just makes to deepening existing problems even further. Thus, it appears that it is not appropriate to use a method used in traditional networks directly in WSNs. The WSNs expect a solution that is always developed uniquely to cover not only their constraints but also their extraordinary capabilities. It is not a good idea for WSNs to adapt conventional methods and approaches, which are introduced to solve different problems other than one in WSNs. The WSN-specific necessities and capabilities are usually ignored in traditional basic buffer management approaches.

Another considerable contribution of this study to the literature is that the proposed solution gives a great flexibility to buffer management solutions by supporting non-predefined priority classes. In order to determine the priorities of transmitted packets, static and dynamic methods exist in current solutions but the priorities to be set must be known in the network in advance. In other words, there is an ambiguity about how packets assigned to a non-predefined priority class should be handled on networks in which well-known buffer management solutions are employed. To overcome this shortcoming, our solution is to allow packets to be assigned to any priority class without any restrictions, so that new priorities can be defined later on the network or, if necessary, the current priorities can be removed from the network. Thanks to this capability, the entire control is delegated to the mechanism that assigns priorities among the packets in the network. This feature is crucial for the network prioritization mechanism to work correctly and consistently. This also points out the necessity of employing a correctly designed prioritization mechanism in the network and all sensor nodes. However, the discussion of this mechanism and its details are beyond the scope of this thesis.

## 5.3 Further Research

In this study, the effects of buffer management solutions on overall performance of the network in context with communication unit were investigated and a comprehensive framework was presented to compare different buffer management solutions. An important finding shown by this research is that buffer management solutions employed on the sensor nodes are one of the main points where unexpected packet losses are experienced during the transportation of packets. The underlying reason of this situation is that the capacity of the memory on the sensor nodes is very limited and it can easily overflow due to WSN-specific traffic characteristics. Other mechanisms, such as memory fragmentation, make this problem even worse. The fragmentation of memory, which is used for differentiation and prioritization of packets in traditional networks, is certainly not appropriate for WSNs. Alternatively, the buffer management solution, which is proposed within this study and called as SQMP, contributes to improving performance by allowing the all capacity of memory to be used unreduced as well as to provide necessary prioritization of packets.

As in memory on the communication unit, similar constraints exist on different units on the sensor nodes. For this reason, the challenges and the limitations at node and network level should be carefully handled in WSNs and the improvement should be done with keeping in mind all interested parties when working on a new approach for WSNs. Otherwise, it should be taken into account that an acceptance or an assumption, which is made carelessly and negligently, can lead to very rapid depletion of critical resources and cause undesired bottlenecks in the network. Therefore, it should be noted that the implementation of traditional and well-known methods directly to WSNs is not a good idea according to this context. It is very clear that there is a necessity for a new and different perspective that moves research ideas in WSNs from current time to the future.

Although our solution brings an important improvement in respect of buffer management solutions in WSNs, there are some points that are overlooked in our solution and need further enhancements. As an example, an important deficiency

which can be encountered in our solution is the lack of a packet drop procedure. In future works, it is planned to integrate an advanced packet drop procedure in which packets that wouldn't be transmitted within their timeout limits could be detected and dropped in advance. It is also planned to make some improvements to ensure that packets having higher importance have higher priorities on the shared medium. It was seen that these deficiencies have a moderate impact on the overall performance of SQMP. Thanks to these improvements, much more packets can be aggregated on the sink node and the high priority packet losses can be reduced.

WSNs have a number of different limitations, but they also offer very important services that are crucial for making and maintaining a new network concept. It should be recognized by the researchers in the field that the unique capabilities, offered by WSNs and not present in traditional networks, are important research areas for the new studies. Some of the main features of WSNs and their unique characteristics could be given as: scalability with respect to the number of nodes in the network, self-organization, self-healing, energy efficiency, a sufficient degree of connectivity among nodes, low-complexity, low size and cost of nodes [67]. Therefore, a new networking approach for WSNs to overcome or alleviate the limitations on the sensor nodes has to be followed. During working on WSNs, it is necessary to be aware of the extraordinary features of such networks and one should have insight on how to manage and solve unexpected inappropriateness between implemented features.

To conclude, this study offers only a small contribution to researches that focus on WSNs and it allows to enable the development of more robust solutions for WSNs by providing a significant awareness on this growing field of research.

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**TOPICS OF INTEREST**

| | | |
|---|---|---|
| - Computer Networks | -Energy Efficiency | -Internet of Things |
| - Wireless Sensor Networks | -Cyber Security | -Algorithms |

**PUBLICATIONS**

Derviş AYGÖR, Shafqat Ur REHMAN, Fatih Vehbi ÇELEBİ, "Impact of Buffer Management Solutions on MAC Layer Performance in Wireless Sensor Networks", IEICE Transactions on Communications, 2018, Volume E101.B, Issue 9, Pages 2058-2068, https://doi.org/10.1587/transcom.2017EBP3389