QoS-AWARE MAC PROTOCOL DESIGN FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

by

M. Aykut Yiğitel

B.S., Computer Engineering, Hacettepe University, 2005

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Computer Engineering
Boğaziçi University
2010

QoS-AWARE MAC PROTOCOL DESIGN FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

APPROVED BY:

Prof. Cem Ersoy (Thesis Supervisor)	....
Prof. Hakan Deliç	....
Assoc. Prof. Can Özturan	....

DATE OF APPROVAL: 06.01.2010

ACKNOWLEDGEMENTS

Firstly, I would like to thank Prof. Cem Ersoy not only for his priceless guidance throughout this thesis but also being the initiator of my academic life. He was always there whenever I encounter a problem during my research as well as in my social life. He is not only a thesis supervisor for me, but also a great person to look up to in every face of the life.

I would like to thank the members of the thesis jury, Prof. Hakan Deliç and Assoc. Prof. Can Özturan for their valuable comments for making this thesis better.

I deeply thank Yunus Durmuş, Atay Özgövde and especially İlker Demirkol for their help, advices and guidance during my research. Without them, it would be too hard to cope with OPNET.

Special thanks to Mustafa Özgur Akduran, Tolga Tolgay, Tolga Önel, Oktay Bilecenoğlu and Tugay Yavuz for their wonderful friendship.

I would like to thank to all my friends in NETLAB (Hande, Rabun, Özlem, Yunus, Sinan, Itır) and SATLAB (Şükrü, Didem, Suzan, Derya, Birkan, Gaye) and all other members of CMPE family that we spent cheerful moments with.

Also thanks for support of my ex branch chief Ltc. Cem Kumsal.

Lastly, thanks to my learned despair Ayla, for her warm smile and everything she did for us.

This work is supported by the Scientific and Technological Council of Turkey (TUBITAK) under the grant number 108E207, by the Turkish State Planning Organization (DPT) under the TAM Project, number 2007K120610, and Bogazici University Research Fund under the grant number 09A101P.

ABSTRACT

QoS-AWARE MAC PROTOCOL DESIGN FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

Growing necessities of the sensory applications has emerged a new subset of Wireless Sensor Networks called Wireless Multimedia Sensor Networks which commonly carry Quality of Service (QoS)-constrained heterogeneous traffic. In order to deliver this heterogeneous traffic in highly resource constrained sensor networks and satisfy their QoS requirements properly, QoS-provisioning becomes unavoidable.

As a result of an extensive survey about QoS-provisioning in sensor networks, QoS perspectives and parameters are investigated and challenging issues are pointed out. Existing MAC protocols are surveyed and followed by QoS-aware MAC protocol design tradeoffs with their advantages and disadvantages. Moreover, Properties of a well-designed QoS-aware MAC protocol are defined.

In this thesis, we propose Diff-MAC; a novel QoS-aware and hybrid priority-based MAC protocol for Wireless Multimedia Sensor Networks. Diff-MAC aims increasing the utilization of the channel with effective service differentiation mechanisms while providing fair and fast delivery of the data. A real-life scenario framed for performance evaluation of Diff-MAC and results obtained through extensive simulations show significant improvements on the performance of the network compared to existing protocols.

ÖZET

TELSİZ ÇOKLU ORTAM ALGILAYICI AĞLAR İÇİN SERVİS KALİTESİ BİLİNÇLİ ORTAMA ERİŞİM KONTROL PROTOKOLÜ TASARIMI

Algılayıcıların kullanıldığı uygulamaların artan gereksinimleriyle birlikte; Telsiz Algılayıcı Ağların (TAA) bir altkümesi olan Telsiz Çoklu Ortam Algılayıcı Ağlar (TÇAA) ortaya çıkmıştır. TÇAA genellikle Servis Kalitesi (SK)-kısıtlı veri taşırlar ve bu veriyi kaynakların bir hayli kıt olduğu TÇAA larda taşımak için SK sağlamak kaçınılmaz bir hal almaktadır.

İlk olarak algılayıcı ağlarda SK sağlanmasıyla ilgili geniş bir inceleme yapılmıştır. SK bakış açıları ve parametreleri ile birlikte karşılaşılması muhtemel sorunlar açıklanmıştır. Ardından mevcut SK-bilinçli Ortama Erişim Protokolleri (MAC) incelenip, SK-bilinçli MAC protokol tasarımında verilmesi gereken kararlar fayda ve zararlarıyla anlatılmıştır. Bununla birlikte, iyi tasarlanmış bir SK-bilinçli MAC protokolün hangi özelliklere sahip olması gerektiği de değerlendirilmiştir.

Bu tezde, TÇAA için Diff-MAC isminde yeni bir SK-bilinçli ve karma öncelik tabanlı MAC protokol önerilmektedir. Diff-MAC adaletli ve hızlı bir şekilde veri taşırken, kanal kullanımını da arttırmayı hedeflemektedir. Gerçek hayatta uygulanabilirliği olan örnek bir senaryo çatılmış ve tüm benzetimler bu senaryoya sadık kalınarak yapılmıştır. Başarım testleri sonuçları, Diff-MAC in varolan MAC protokollerinden daha başarılı olduğunu göstermiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

A_t	Number of transmission attempts
A_c	Number of collisions
d	Distance between the transmitter-receiver
d_0	Reference distance
f	Packet size in bytes
K	Camera frame rate
L	Length of surveillance area
n	Path loss exponent
N	Number of sensor nodes
$p(d)$	Probability of successfully receiving a packet at the distance d
P_c	Probability of collision
P_n	Noise floor
P_r	Received signal strength
P_t	Transmitter output power
$PL(d)$	Path loss at the distance d
$PL(d_0)$	Path loss at the reference distance d_0
$SNR(d)$	Signal to noise ratio at the distance d
TA	Active time
T_c	Observation duration for contention window size adaptation
T_d	Observation duration for dynamic duty cycling
T_{dwell}	Dwell time
W	Width of surveillance area
X_σ	Zero-mean Gaussian random variable with standard deviation σ
$\overrightarrow{V}$	Target velocity

α	Contention window size adaptation coefficient
ϱ	Number of transmission attempt threshold
δ	Number of processed packet threshold
σ	Shadowing variance

ACK	Acknowledgement packet
BE	Best Effort
CCF	Congestion Control and Fairness
CF	Control Frame
COA	Camera Orientation Angle
CODA	Congestion Detection and Avoidance
CP	Contention Period
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
CW	Contention Window
DATA	Data packet
DC	Duty Cycle
DF	Data Frame
DiffServ	Differentiated Services
DoF	Depth of Field
FIFO	First In First Out
FoV	Field of View
FPS	Frame Per Second
GPS	Generalized Processor Sharing
GPSR	Greedy Perimeter Stateless Routing
IFS	Inter Frame Space
IntServ	Integrated Services
ITU	International Telecommunication Union
JPEG	Joint Photographic Experts Group
LPRA	Loosely Prioritized Random Access

MAC	Medium Access Control
MPEG	Moving Picture Experts Group
NRT	Non-Real-Time
PCCP	Priority Based Congestion Control Protocol
PL	Priority Level
PORT	Price-oriented Reliable Transport Protocol
PSR	Probability of Successfully Receiving a Packet
RL	Reinforcement Learning
RNG	Relative Neighborhood Graph
RT	Real-Time
RTS	Request to Send
SF	Super Frame
SQCIF	Sub Quarter Common Intermediate Format
SS	Short Space
TDMA	Time Division Multiple Access
TF	Time Frame
TNHB	Traversed Number of Hops Based
TP	Transmission Period
QoS	Quality of Service
WFQ	Weighted Fair Queueing
WMSN	Wireless Multimedia Sensor Network
WSN	Wireless Sensor Network

1. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of small sensor devices capable of communicating through the wireless medium and gather information related to the phenomena under observation [1]. Current sensor technology enables sensor devices to gather information such as temperature, humidity, light, acceleration, radioactivity, sound, vibration, pressure, magnetic field. Main idea behind the WSNs is collecting the required information from stand-alone sensor nodes previously deployed to the area of interest and generate a global view for the observer by relaying this information to an aggregation point called sink as seen in Fig. 1.1. Battlefield or border surveillance, target tracking, environmental control, habitat monitoring, industrial process control, health care delivery can be counted as examples of WSN application fields. Although recent developments about low-cost and tiny hardware fabrication improved the capabilities of the sensor devices, WSNs are still highly resource constrained networks in terms of energy, bandwidth, memory and processing power.

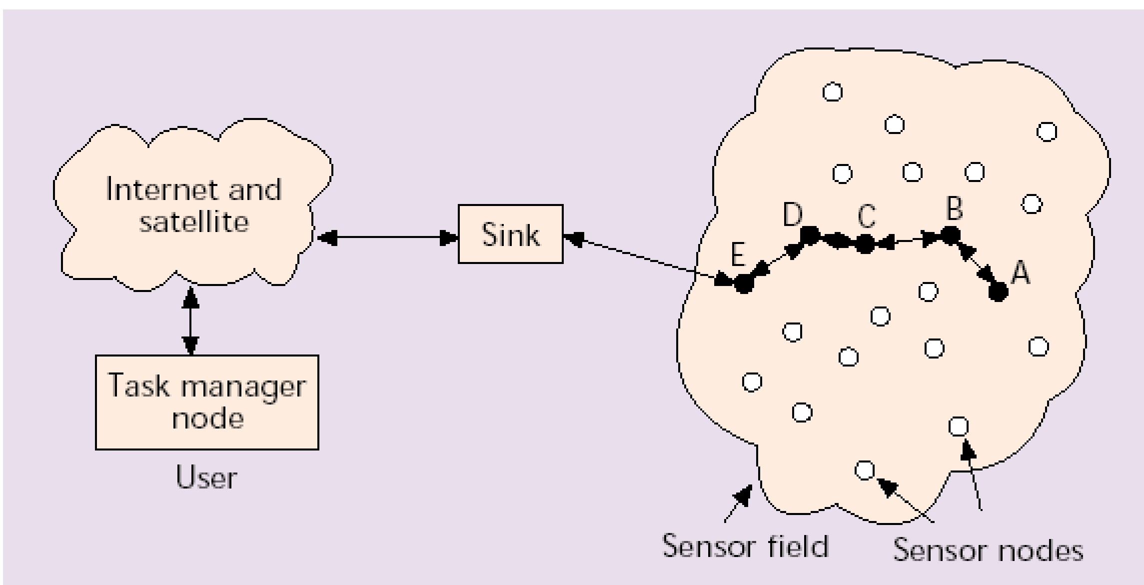


Figure 1.1. Sample WSN architecture [1]

Popularity of wireless sensor networks combined with the multimedia requirements of new applications have enabled Wireless Multimedia Sensor Networks. WMSNs are composed of embedded cameras and microphones besides traditional scalar sensors and generally carry heterogeneous, quality of service (QoS)-constrained traffic such as video and audio streams, still images and scalar data [2]. Since WMSNs are used in more bandwidth-hungry applications with respect to WSNs, operating under severe resource constraints becomes more challenging. Moreover, in order to create a better global view of the observed phenomena or support latency-intolerant real-time applications, QoS support mechanisms become necessary for WMSNs.

Although the term QoS is widely used in the area of computer networks, there is still an uncertainty in what exactly QoS means. However, the simple model depicted in Fig. 1.2 may be considered as a common ground. It is certain that, QoS support is provided in response to particular requirements of the customer who will be given the service. International Telecommunication Union (ITU) [3] has defined QoS as: *"Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service"*. Traditionally it refers to control mechanisms that orchestrate the resource reservation rather than the provided service quality itself. Simply or practically, QoS brings the ability of giving different priorities to varied users, applications, and data flows, frames or packets based on their requirements by controlling the resource sharing, hence achieving higher level of performance over others. However, the meaning of the QoS can vary based on the application-specific needs and an accurate definition might be done for each implementation according to its specific characteristics.

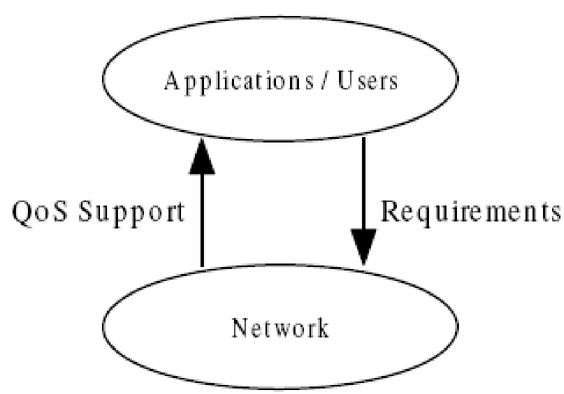


Figure 1.2. A simple QoS model [65]

In case of WMSNs that deliver various types of traffic, QoS support mechanisms are required to prioritize and manage the resource sharing according to the requirements of each traffic class. In order to meet these requirements, WMSNs need novel and well-designed QoS support mechanisms in each layer of the communication protocol stack since envisioned applications are dissimilar to traditional end-to-end applications. Especially real-time multimedia and mission-critical applications brought forward new QoS requirements since they need delay-bounded and reliable delivery of the data. Moreover, additional characteristics of WMSNs such as resource constraints, dynamic topology, interaction with the environment make the QoS support much more challenging than in others.

The variety of the applications and requirements of these applications make implementation of a *one-size-for-all* QoS-support mechanism impossible. However, well-defined requirements help to reveal the essential QoS parameters for a specific application. Identified QoS parameters can be used to provide efficient QoS support and this brings the ability of measuring the performance of the provided QoS support.

Since MAC layer of the communication protocol stack rules the sharing of the medium and all other upper-layer protocols are bound to that, MAC layer has the ability to affect the overall performance of the WMSNs. That's why, MAC layer becomes a proper choice to implement QoS support in and dominates the performance of the QoS-support relative to other layers. Besides, resource constrained and topologically dynamic nature of the WMSNs make the MAC layer more important than it is in the traditional networks.

In this thesis, we propose Diff-MAC; a new QoS-aware and priority-based MAC protocol for WMSNs. Diff-MAC is designed with key features to support service differentiation and QoS provisioning to deliver heterogeneous traffic. These features include: i) fragmentation & message passing, ii) adaptive contention window adjustment, iii) adaptive duty cycling, iv) intra-node & intra-queue prioritization. Diff-MAC is an all-in-one QoS-aware MAC protocol proposed for WMSNs that dynamically adapts the use of its resources to meet the requirements of different traffic classes. We evaluate the performance of Diff-MAC with extensive simulations for three different classes of traffic co-existing in the network: real-time (RT) multimedia traffic, non-real-time

(NRT) traffic and best effort (BE) traffic, and compare its performance with SMAC and another QoS-aware MAC protocol proposed for WMSNs [7]. The following are some of the key contributions of this work and highlights of Diff-MAC:

- The built-in fragmentation and message passing feature of Diff-MAC fragments the long video frames into smaller video packets and reserves the medium to send these packets as a burst which in turn reduces the retransmission cost of long messages in case of MAC failures.
- Diff-MAC can adjust its contention window (CW) according to the dynamic traffic requirements to reduce the number of collisions and keep the size of the contention window as small as possible in order to avoid unnecessary waiting time to reserve the medium and accordingly to balance both energy consumption and delay.
- Diff-MAC adapts its duty cycle (DC) according to the dominating traffic class in the network. For instance, due to the stringent delay requirements of real-time multimedia traffic, sensor nodes adapt a higher duty cycle whereas if the flowing traffic has a best-effort characteristic, sensors adjust their duty cycles to lower levels to conserve energy.
- Intra-queue and intra-node prioritization feature of Diff-MAC provides fair delivery of the data among all sensor nodes and among all traffic classes respectively to avoid intolerable performances.
- Diff-MAC exhibits better performance in terms of delay and delivery rate for RT and NRT traffic while it keeps the energy consumption at an acceptable level, and it exhibits better energy efficiency in terms of BE traffic while it keeps the delay at lower levels compared with SMAC and the MAC protocol proposed in [7].

The organization of this thesis is as follows: In Chapter 2, inspiring from the motivations asserted above, we will mention about QoS perspectives and classify the application fields of the WMSNs. Further, we will define the specific requirements of these application classes and try to point out parameters for the performance evaluation of QoS support. Challenges for QoS-Provisioning in sensor networks and concepts of service differentiation will be examined. Existing QoS-aware MAC protocols will be surveyed extensively and MAC layer design tradeoffs will be pointed out. Properties of a well-designed QoS-aware MAC protocol will conclude the Chapter 2. In Chapter 3, design and architecture of Diff-MAC will be explained in detail. In Chapter 4, a real-life scenario will be introduced to make an accurate performance evaluation of the derived protocol. System model and simulation parameters will be listed and followed by a comparative performance evaluation of Diff-MAC. Chapter 5 concludes this thesis and provides possible directions for future research.

2. QoS PROVISIONING IN WIRELESS MULTIMEDIA SENSOR NETWORKS

2.1. QoS Perspectives and Parameters

In WMSNs, QoS perspectives can be classified as *Application-specific* and *Network-specific*. However, this separation cannot be absolute because both perspectives must be considered together in order to make a reliable measurement of the overall network performance.

Application-specific QoS: These are the application specific requirements that imposed by the application itself such as lifetime [54, 55], coverage [56], deployment, quality of the sensing, camera resolution, number of active sensors. In other words, application-specific QoS directly affects the quality of the application.

Network-specific QoS: These are the underlying communication network specific requirements which are related to the delivery of the QoS-constrained data. From this perspective, we utilize the network resources efficiently in each layer of the communication protocol stack and fulfill the QoS requirements of the sensor data imposed by the application. Hence, we will be interested in this perspective of the QoS in the rest of this work.

In order to make an accurate performance evaluation of the proposed QoS-mechanisms, we have to point out the requirements of the applications and map these requirements to a set of QoS parameters. Since WMSNs can be used in many fields, these requirements are highly dependent on the application itself. Consequently, at first, a classification of WMSN applications has to be made.

Since applications that use the same data delivery model/models mostly have common requirements, we will work on the applications classified by their data delivery models as in [52]. These models are event-driven, query-driven, continuous and hybrid.

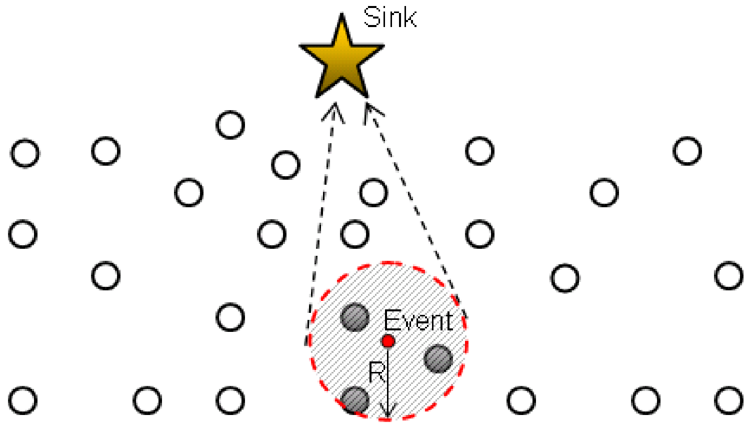


Figure 2.1. Event-driven data delivery model in WSN

Event-driven: Success of the event-driven applications is bound to the quality and accuracy of the observation related to the observed phenomena with reliable and fast delivery of the information about the detected event. In the majority of the cases, more than one sensor nodes detect the event and generate related data as seen in Fig. 2.1. Therefore, data is mostly delivered from many sources to sink in the event-driven applications. Also, creation of highly redundant and bursty traffic is very likely to be seen in the event-driven applications since the same event can be detected by many sensor nodes.

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

Continuous: In this model, sensor nodes send their data to the sink continuously for real-time traffic such as voice, video or periodically for non-real-time traffic. Delivery of the real-time data is delay-intolerant and requires a certain level of bandwidth. Also packet losses are tolerated only in a limited threshold. For periodically collected non-real-time data, latency and packet losses are tolerable.

Hybrid: Two or more of the mentioned data delivery models coexist in the hybrid model and carried traffic is mostly heterogeneous. For improving the overall performance of the network, carried traffic must be classified and requirements of these traffic classes must be satisfied.

For the applications that use event-driven data delivery model, reliability gains importance since notification of the detected event might be crucial like a forest fire, tsunami or earthquake. Also this notification must be delivered as quickly as possible in order to take the necessary precautions.

The nature of the query-driven applications are very similar to event-driven and the same metrics are valid. Additionally, queries submitted from the sink must be transmitted to the related sensor nodes as reliable and as fast as possible.

Continuous applications collect information from sensor nodes periodically. That's why, this kind of applications require relatively higher throughput. In case of data-streaming multimedia transmission, packet loss must be lower than a certain threshold while it can be tolerable for non-real-time data. Moreover, delay jitter is very important for real-time data-streaming applications since receiver-side buffering might be necessary for application-specific QoS requirements.

Since each carried traffic class requires a particular data delivery model, hybrid applications commonly carry heterogeneous traffic. That's why, carried multiple traffic classes must be differentiated based on their special characteristics and must be treated accordingly. Important QoS parameters for each application class are summarized in Table 2.1.

2.2. QoS Challenges

WMSNs inherit most of the well-known QoS challenges from traditional wireless networks. However, WMSNs have some unique characteristics such as severe resource constraints and interaction with the environment that pose additional challenges for

Table 2.1. Important QoS Parameters for Application Classes

	Event Reporting Reliability	Latency	Throughput	Packet loss	Delay jitter
Event-driven	√	√			
Query-driven	√	√			
Continuous		√	√	√	√
Hybrid	√	√	√	√	√

QoS-Support. These QoS challenges for WMSNs can be listed as follows:

- *Resource constraints:* WMSNs lack of bandwidth, memory, energy and processing capability. However, limited energy is the most crucial one since in many scenarios it is impossible or impractical to replace or recharge batteries of the sensor nodes. Although solar energy [57, 58] seems to be a promising solution to energy scarcity, present solar panels are still too big for tiny sensor devices. Also limited processing capability, bandwith and memory add extra challenges. Eventually, proposed QoS support mechanisms must be lightweight and simple in order to operate on a highly resource constrained sensor node and prolong the network lifetime.
- *Node deployment:* Deployment of sensor the nodes may be either deterministic or random. In deterministic deployment, sensor nodes are placed by hand and routing can be done by pre-scheduled paths. In random deployment, sensor nodes are deployed randomly and organize themselves in an ad hoc manner. Hence, neighbor discovery, path discovery, geographical information of the nodes and clustering will be an issue to be solved.
- *Topology changes:* Node mobility, link failures, node malfunctioning, energy depletion or natural events like flood or fire can cause topology changes. Moreover, most of the link layer or MAC layer protocols employ sleep-listen schedules and turn the radio of the sensor nodes off temporarily for energy saving. This kind of power management mechanisms also cause temporary topology changes. Inevitably, dynamic nature of the WMSN topology brings an extra difficulty to the QoS support.

- *Data redundancy:* WMSNs comprises of large amount of tiny sensor nodes and that's why observed event or phenomena can be detected by several sensor nodes. Although this redundancy helps the reliable data delivery, it also causes unnecessary redundant data in the network and yields to congestion. Data aggregation/fusion [59, 60] mechanisms may decrease the redundancy but also may introduce additional delay and complexity to the system. Hence, effective QoS mechanism needed to cope with the data redundancy.
- *Multiple traffic types:* Sensor nodes which have the capability of sensing or observing various phenomenons can generate different types of traffic. For instance, streaming multimedia, location of a detected target or periodic temperature information of an area might be carried at the same time for a specific application. Therefore, applications requiring existence of multiple traffic classes add extra challenging issues to QoS support since requirements of each traffic class differ.
- *Real-time traffic:* In some critical applications like natural disaster monitoring or security surveillance, gathered data is valid only for a limited time frame and has to be delivered before its deadline. This type of critical real-time data must be handled by adequate QoS mechanisms.
- *Unbalanced traffic:* There must be a central entity that obtains the global view of the sensing environment or middle layer entities relatively more powerful than sensor nodes for data aggregation and compression which are named as sink or clusterhead. Existence of single or multiple sinks in the WMSNs causes unbalanced traffic flows from sensor nodes to sink nodes. Although smart routing protocols share the traffic load between different routes, it is still an issue to be handled.
- *Scalability:* Most of the sensor networks comprises of hundreds or thousands of sensor nodes. As area of interest or requirements for the quality of observation increases, more sensor nodes need to be deployed. Therefore, designed QoS mechanism must scale well even highly dense or large networks.

Challenging issues related to WMSNs are pointed out. Although its very hard to bring proper solutions for each of these challenging issues at the same time, these factors must be taken into account during the design of a new QoS-support mechanism and novel techniques have to be adopted to cope with them.

2.3. Service Differentiation

Service differentiation is also known as traffic engineering and constitutes the most fundamental part of the QoS provisioning since existence of single service class may lead to unpredictable network conditions during peak or bursty traffic. There are two types of service differentiation models in conventional computer networks, integrated services (IntServ) [70] and differentiated services (DiffServ) [71]. Aim of both of the differentiation models are to map assigned flow (IntServ) or packet (DiffServ) priorities into service qualities on the shared resources.

IntServ Model: This model maintains service on a per-flow basis and can be considered as a reservation-based approach. Flows can be divided into two categories as data-centric or host-centric where an example of the data-centric flow can be the information generated by the motion sensors from a commonly used breach path in a border surveillance application and host-centric flow can be the stream of packets between a particular source and destination. However, it is very hard to maintain the per-flow states of the sensor nodes in highly resource constrained sensor networks. Moreover, IntServ model requires a reliable in-band or out-of-band QoS signaling within the network for resource reservation which is also very hard to assure in WSNs.

DiffServ Model: This model maintains service on a per-packet basis and can be considered as reservation-less. In DiffServ model, QoS support achieved by some methods such as traffic classification, queuing and packet scheduling. Since every network entity will behave as both source and relay in multihop sensor networks, the disadvantage of the DiffServ model is costly memory requirement.

Even though IntServ and DiffServ are defined as separate models, they can be used together for some sort of specific applications as well. This hybrid models try to take advantage of IntServ model by using per-flow and DiffServ model by using per-class differentiation.

Since WSNs operate in a multi-hop manner, lightweight and easy to implement DiffServ model can be adapted to easily. Each packet will have a degree of importance and this will be apparent for every entity of the network. In this way, each layer of the communication protocol stack will treat the packet by the way its priority imposes. For this reason, DiffServ model will be assumed as the default service differentiation method for the rest of our work and mentioned traffic classification, queuing and packet scheduling methods will be explored in detail.

2.4. Literature Review

In the literature, there are many protocols proposed for wireless networks [23–25] to provide QoS support mechanisms; however sensor networks have additional challenges and constraints with respect to traditional wireless networks like random and mostly redundant deployment, severe resource scarcity, high node density [1]. Therefore, there is a growing necessity for resource efficient QoS-aware MAC protocols which will enable WMSNs to operate more efficiently. Although there are many WSN MAC layer proposals [11–17], most of them mainly focus on energy efficiency and channel utilization leaving the QoS perspective aside while very few of them regard QoS provisioning [4–9]. Although there are some proposals for real-time WSN communication [26–28], these are not applicable to WMSNs that carry multiple types of traffic.

Since energy scarcity is the most important problem in sensor networks, SMAC [11] tries to reduce the energy consumption of the sensor nodes by integrating sleep-listen schedules by turning the radio of the nodes off and on. WiseMAC [12] uses non-persistent CSMA with preamble sampling to decrease idle listening which is listed in [1] as one of the primary factors for energy waste. TRAMA [13] is a TDMA based protocol and uses a distributed election algorithm to select the next transmitter within each two-hop neighborhood. SIFT [14] is proposed for event-driven applications and tries to relay the first reports of an event as fast as possible. DMAC [15] tries to achieve low latency by assigning the transmission slots based on a data gathering tree. T-MAC [16] integrates dynamic sleep-listen periods to adapt the variable traffic loads and tries to solve the early sleeping problem.

In the literature, there are many protocols for QoS provisioning at the network layer [33–40]. SWAN [33] uses feedback information from the MAC layer to regulate the transmission rate of NRT traffic in order to sustain RT traffic. RAP [34] calculates the velocity of the packet based on its deadline and destination so that a high velocity packet can be delivered earlier than a low velocity one. SPEED [35] protocol is designed to provide soft end-to-end deadline guarantees for real-time packets in sensor networks and ensures the speed of the packet until its destination. MMSPEED [36] provides QoS levels in two domains which are timeliness by guaranteeing multiple packet delivery speed options and reliability by probabilistic multipath forwarding.

Integration of a reliable and fair transport protocol improves the QoS support for multimedia applications. One of the main objectives of the transport layer in WMSNs is congestion control. As congestion indicator, queue's proportional load [41, 42, 49], packet service time [43] and ratio of service time over packet inter-arrival time [44] used in previous works. In the literature, there exist some proposals [41–49] to avoid congestion and maintain reliable transmission. Congestion control and fairness (CCF) was proposed in [44] and uses a distributed algorithm to eliminate the congestion and provide fair delivery of the packets to the sink. Priority based congestion control protocol (PCCP) was proposed in [43] and uses both introduced congestion degree and sensor node priority index to control congestion. Price-oriented reliable transport protocol (PORT) [47] minimizes energy consumption while achieving necessary level of reliability. The term reliability is used as assurance of the sink to obtain enough information about the phenomenon under observation rather than the ratio of the successful delivery. Congestion detection and avoidance (CODA) [49] detects congestion by monitoring the buffer occupancy and measuring the channel load. Once congestion is detected, the sensor node broadcasts a suppression message to its neighbors and tries to mitigate the congestion. Yaghmaee et al. [45] propose a priority-based rate control mechanism for congestion control and service differentiation in WMSNs. Their algorithm distinguishes high priority RT traffic from low priority NRT traffic, and treats the processed traffic based on its priority.

In this section, existing QoS-Aware MAC protocols for WMSNs will be surveyed extensively to illuminate the path to design of a novel one. At the end of the literature survey, Table 2.2 will summarize the specific properties of the examined QoS-Aware MAC protocols.

2.4.1. PSIFT

PSIFT [4] is a QoS-aware MAC protocol designed for event-driven applications and based on SIFT by Jamieson et al. [14]. The motivation behind SIFT is that when an event is sensed, the first R of N potential reports is the most crucial part of the messaging and has to be relayed with low latency. Relayed R reports will be sufficient for the sink node to accurately identify the event and elimination of redundancy decreases both probability of collision and latency. They proposed two methods “Explicit ACK” and “Implicit ACK” for suppressing unnecessary redundant reports based on the broadcast nature of wireless transmission.

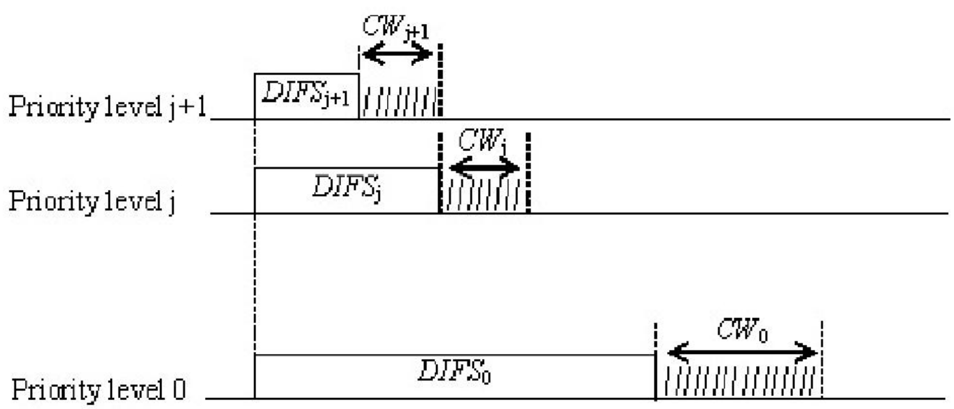


Figure 2.2. Service differentiation in PSIFT [4]

PSIFT is a Carrier Sense Multiple Access (CSMA)-based MAC protocol and provides traffic differentiation by varying the inter frame space (IFS) and contention window (CW) size for each traffic class as seen in Fig. 2.2. They Prioritize the traffic classes in a dynamic manner based on the traversed number of hops, i.e. the higher number of hops traversed, the higher level of priority that a packet has.

Advantages and disadvantages: Although PSIFT might be a sensible choice for event-driven applications it is nearly impossible to be used in any other type of applications. Besides, removal of the redundancy may result in unreliable data delivery since identification of reports belonging to separate events will be an issue to be solved. Report suppression mechanism decreases the traffic load in the network and leads to mostly idle sensor nodes. This advantage of the PSIFT must be utilized to decrease the energy consumption of the network by integrating a kind of sleep-listen schedule.

2.4.2. Q-MAC

Q-MAC [5] utilizes intra-node scheduling to select the next serviced packet from five different priority queues and inter-node scheduling to coordinate the medium access among multiple neighboring nodes as seen in Fig. 2.3. The priority of an incoming packet is determined by two factors. Application layer perspective gives priorities based on the content of the packet and MAC layer based on traversed hop count. By this way, packets are mapped into predefined five different priority queues including one instant queue that any packet in this queue served immediately. Within the context of intra-node scheduling, MAX-MIN fairness algorithm [31] used to control the rate and packetized Generalized Processor Sharing [32] algorithm used to select the next transmitted packet. For inter-node scheduling, a novel protocol named Loosely Prioritized Random Access (LPRA) proposed for coordinating the medium access based on the transmission urgencies of the packets waiting to be transmitted. There are four factors determining the transmission urgency i.e. priority of the packet: packet criticality from the application point of view, traversed number of hops, remaining energy of the sensor node and queue's proportional load.

A Frame represents single RTS-CTS-DATA-ACK packet exchange and consists of contention period (CP) and transmission period (TP). Fig. 2.4 depicts the CPs of different priority levels (PL) and the non-uniform probability distribution for selecting a CW slot. As congestion control mechanisms, doubling the CW size proposed for decreasing the probability of collision and decreasing the packet deadline for alleviating the traffic load. For energy efficiency, sensor nodes follow sleep-listen schedules with fixed duty cycles.

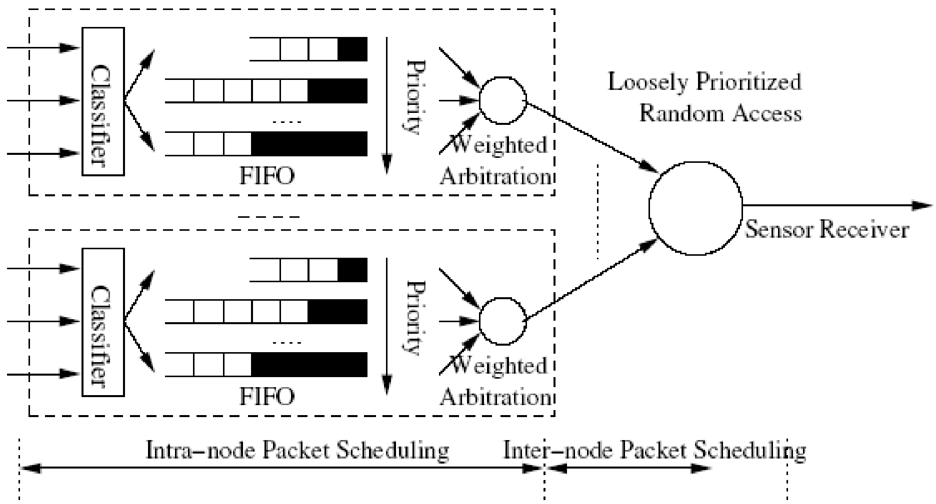


Figure 2.3. The multi-queue architecture of Q-MAC [5]

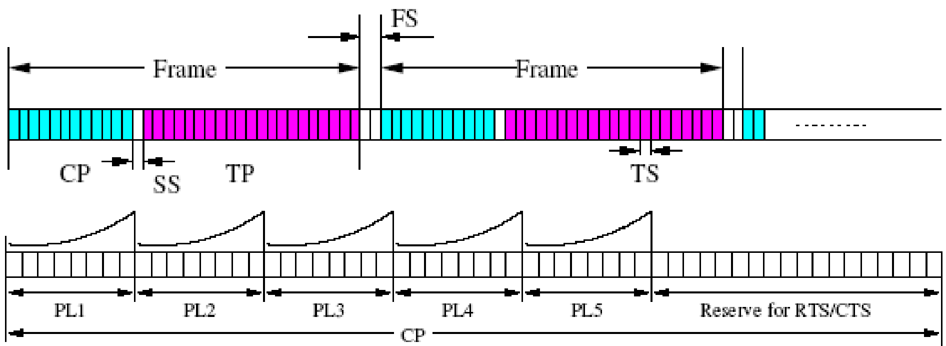


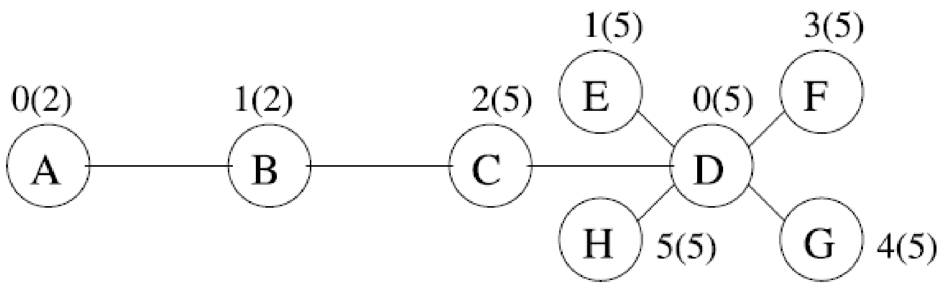
Figure 2.4. Frame structure and prioritized CP of Q-MAC [5]

Advantages and disadvantages: Dynamic priority assignment provides robustness against changing conditions of the sensor network. However, calculation of the transmission urgency of the packet is relatively complex. Integration of the increasing geometric probability for CW selecting may decrease the collision rate but also may result in higher latencies.

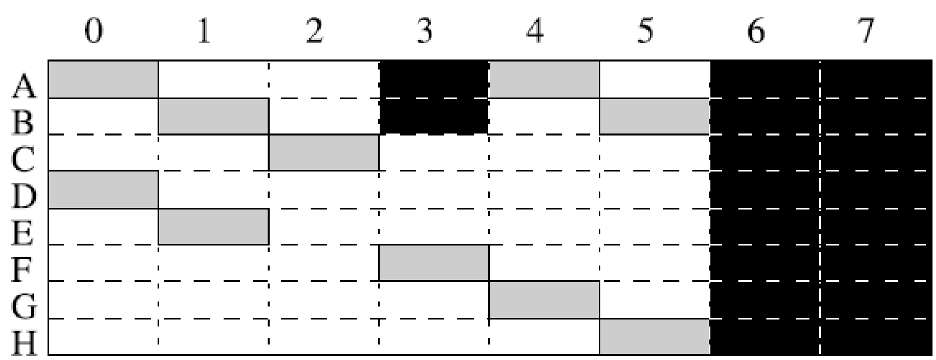
2.4.3. PQ-MAC

PQ-MAC [6] aims to use advantageous features of both contention based and schedule based approaches and proposes a hybrid scheme for medium sharing. Global clock synchronization, neighbor discovery and accordingly slot assignment are done during the setup phase and followed by the transmission phase which real data delivery takes place.

Slot assignment within the setup phase regards the two hop distance neighbor nodes and allocates different time slots based on the DRAND [29] algorithm as seen in Fig. 2.5. Frame size of the protocol determined by the Time Frame (TF) rule of the Z-MAC [30] and similarly depends on the two-hop neighborhood of the sensor node. Owner sensor node of a specific transmission slot assigned in the setup phase has an exclusive right to send data in it. If the owner of the slot does not have any data to send or has lower priority data, non-owners of the slot can contend for the slot based on priorities of their data.



(a) Network topology



(b) Slot scheduling

Figure 2.5. The slot scheduling of PQ-MAC by TF rule [6]

The super frame (SF) structure of the PQ-MAC can be seen in Fig. 2.6 and consists of two sub frames: Data frame (DF) which is used for data delivery and Control Frame (CF) which used for sleep-listen schedule. Adaptive sleep-listen schedule used for energy efficiency and synchronization between neighboring sensor nodes provided by generating sequence of bits indicating whether it will sleep or be awake during the corresponding time slot. In Fig. 2.7, medium access prioritization mechanism can be seen for three different traffic classes. Only the owner of the slot can access privileged contention windows T0, T2 and T4 while non-owners can contend during T1, T3 or T5 with respect to their traffic types.

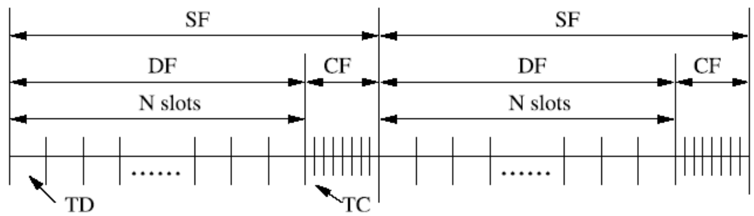


Figure 2.6. The super frame structure of PQ-MAC [6]

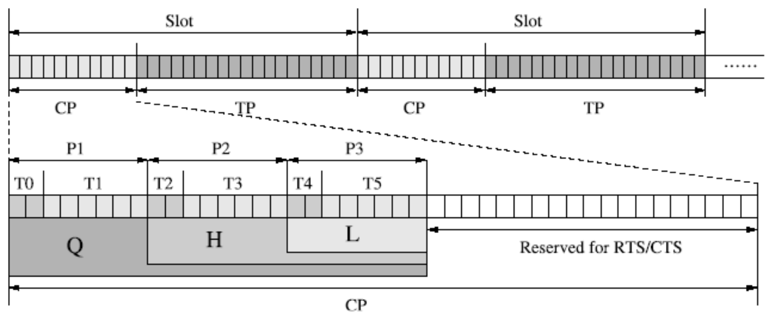


Figure 2.7. The slot structure of PQ-MAC [6]

Advantages and disadvantages: Neighborhood of the sensor nodes, relay nodes or cluster heads can change frequently because of the dynamic nature of the WSNs as mentioned earlier. That's why, permanence of the slot assignment accuracy which is done once at the beginning of the setup phase severely effected. In heavy traffic conditions, PQ-MAC behave like a Time Division Multiple Access (TDMA) based protocol since almost all nodes will have a packet to send and use its own transmission slot. This improves the channel utilization and reduces the probability of collision significantly at the cost of tight clock synchronization.

2.4.4. Saxena et al. MAC

The closest work to ours is introduced by Saxena et al. [7] [10] where they use a CSMA/CA approach and assume three types of traffic carried in the network: streaming video, non-real-time (NRT) and best effort (BE). Basically, their MAC scheme periodically monitors the dynamics of the sensor nodes and the medium, and collects relevant network statistics like transmission failures and transmitted traffic type. Accordingly, the protocol updates the CW size adaptively, based on the gathered information. CW adaptation is performed in a "stop-for-a-round" fashion and differentiation is provided by varying the up and down scale factors for different traffic classes. Consequently, CW size for higher priority traffic decreases faster than the lower priority where an increase is performed more slowly. Duty cycle is adjusted directly according to the dominating transmitted traffic from a sensor node as seen in Fig. 2.8. Although, CW size and duty cycle adaptation are common features between our protocol and Saxena et al. MAC, we use a different approach for CW size adaptation. Saxena et al. MAC waits for other sensor nodes to adjust their CW size whereas Diff-MAC continuously adapts the CW size regardless of the neighboring sensor nodes, hence achieves better CW sizes faster than Saxena et al. MAC. Additionally, Saxena et al. MAC uses a FIFO based queuing method to process packets from different priorities where we utilize a packetized weighted fair queuing method which brings the ability of controlling the medium access, hence relative throughput, for each traffic class. Additionally, Diff-MAC uses a "traversed number of hops based prioritization" scheme to prioritize the packets according to their generation times and to deliver them as quickly as possible to the sink node, whereas Saxena et al. MAC does not differentiate the packets from the same class and always processes the packets according to the priority of their traffic type.

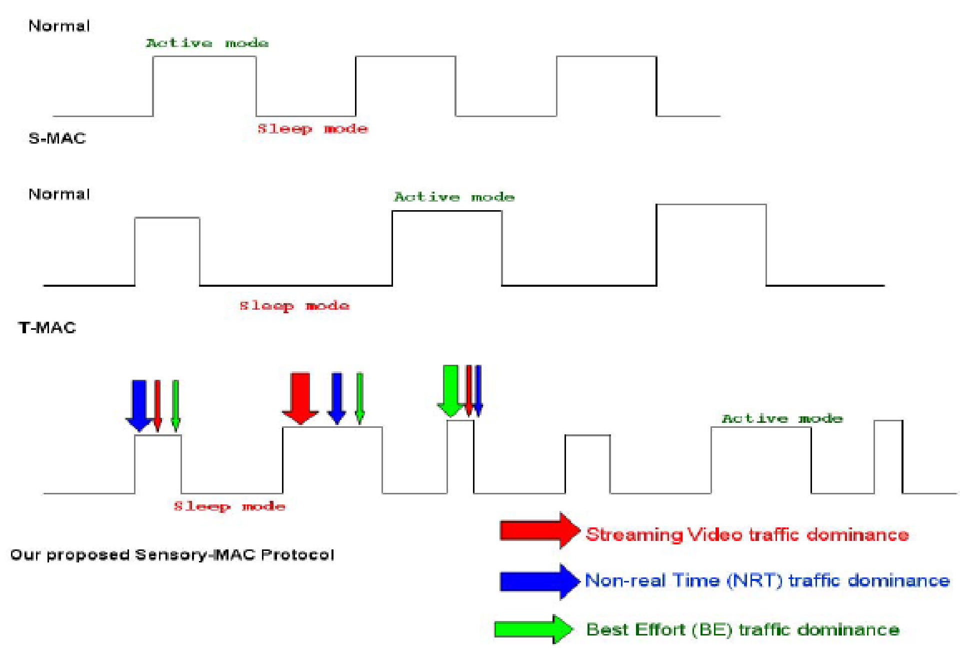


Figure 2.8. Duty cycling in Saxena et al. MAC [10]

Advantages and disadvantages: Since sensor nodes have to wait for others to further adjustments, stop-for-a-round adaptation of CW size may result in inaccurate adjustments or very slow convergence to target CW size. Moreover, using the same packet format for every traffic class might be a waste of limited resources because scalar data and video frames will not be at the same size probably.

2.4.5. RL-MAC

RL-MAC [8] is a QoS-aware reinforcement learning (RL) based MAC protocol and uses a CSMA scheme. It adaptively changes the duty cycle of the sensor nodes based on not only local observations but also neighbor nodes. As a local observation, the number of successfully transmitted and received packets during the active time period is recorded to be used in the duty cycle adaptation with proportional load of the queues. For neighbor observation, a field is added to the packet header to provide information to the receiving node regarding the number of failed transmission attempts by the sender. With this field, RL-MAC tries to save energy while minimizing the number of missed packets due to early sleeping. Three traffic categories are defined and service differentiation between them is implemented by varying the CW size of each class. Although the algorithm includes various features for QoS-constrained traffic, using complex reinforcement learning algorithms might not be feasible for resource constrained sensor nodes.

Advantages and disadvantages: Relatively complex RL based algorithm adapts the network conditions very well but might not be feasible for energy and processing power constrained sensor nodes.

Table 2.2. Comparison of QoS-Aware WSN MAC Protocols in the Literature

Protocol	**Type**	**CW**	**IFS**	**Priority Assignment**	**Adaptivity to Changes**	**Energy Awareness**	**Complexity**
PSIFT [4]	CSMA	Variable (Fixed for each priority)	Variable	Hybrid	Weak	No	Low
Q-MAC [5]	CSMA	Fixed	-	Hybrid	Good	No	Medium
PQ-MAC [6]	TDMA/CSMA	Fixed	-	Static	Weak	Yes	High
Saxena et al. [7]	CSMA	Variable	Variable	Hybrid	Good	Yes	Medium
RL-MAC [8]	CSMA	Variable (Fixed for each priority)	-	Static	Good	Yes	High

2.5. MAC Layer Design Tradeoffs

2.5.1. CSMA vs. TDMA Schemes

Both Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) methods have advantages and disadvantages. One of the main drawback of TDMA scheme is its necessity to tight clock synchronization to prevent transmission slot violations originated from clock shifting. A centralized or distributed slot assignment algorithm also needed in TDMA to decide on which sensor node will transmit its packet in which transmission slot. Moreover, TDMA must have information about the sensor nodes and their positions in order to make a proper slot assignment. Although some instances of TDMA scheme just require the information of neighboring sensor nodes, they still need a neighbor discovery operation.

Having the topological information of the network or neighbor discovery is not sufficient for slot assignment in the long term. Depletion of energy resources, hardware malfunctioning, node mobility, link failures or natural events like flood or fire cause frequent topology changes in WSNs and up to date state of the network must be obtained periodically for accurate slot assignment in TDMA based schemes. Consequently, as the size of the network increases, TDMA does not scale well.

The most essential advantage of the TDMA scheme is high channel utilization, in other words, high throughput since wireless medium becomes totally collision-free. As a result of the slot assignment mechanism, the channel is continuously used by the sensor nodes. Since every sensor node knows when to transmit, integration of a sleep-listen schedule can provide significant energy saving also.

On the other hand, CSMA scheme is very easy to implement and does not require any additional information related with the network topology. Also performance of the CSMA is not as dependent as TDMA on the network topology and scales well if network size or density increases. However, efficient back-off strategies must be employed in CSMA to alleviate the collisions and this brings an extra latency.

2.5.2. Static vs. dynamic priority assignment

Priority assignment methods that imply the criteria of the differentiation need to be identified carefully in order to achieve fair and effective QoS support. Since the correctness and accuracy of the assigned priorities affect the QoS-support significantly, overall performance of the QoS mechanisms highly depends on priority assignment methods. In the literature, priority assignment methods are divided into two categories.

Static priority assignment: If the priority is assigned once the packet is created and never changes until its destination, it is called as static priority assignment. There are several criteria proposed for static prioritization previously:

- Traffic class: Packets can be prioritized based on the type of traffic like real-time, non-real-time, best effort. By this way, delay bounded real-time packets will have higher priority whereas delay tolerant non-real-time and best effort packets have lower.
- Source type: QoS mechanism can specify set or sets of sensor nodes or sinks which generates more important data than others and assigns all WSN entities a priority. Then, the node which generates the packet also gives the priority of itself to that packet, i.e. packet inherits the priority of its creator. The static priority of the network entities can be given based on the sensor types, observed area characteristics, distance to center etc.
- Data delivery model: There are four types of data delivery model in WSNs as discussed in Section 2.1. Priority of the packets can be selected based on the belonging data delivery model. For example, event-driven data might have higher priority than query-driven in case of an intrusion detection algorithm.

Dynamic priority assignment: Contrary to static assignment, packet priorities may vary during the delivery. Decision parameters for priority differentiation can be listed as follows:

- Remaining hop count: Remaining number of hops to the destination of the packet can be used as a parameter for packet prioritization. One of the ideas behind this parameter is minimizing the delay deviations between the packets generated by the sensor nodes which have different distances to the sink. Also, as the packet traverses more hops it becomes more vulnerable to deadline miss, dropping and link failure. Hence, packets which will traverse more hops until the destination are given higher priority.

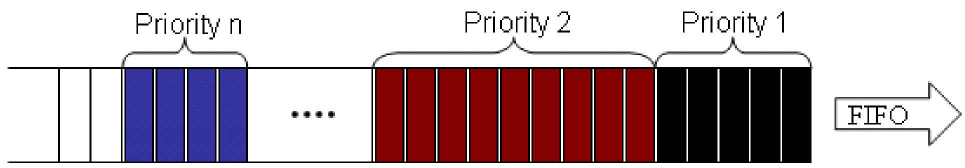
- Traversed hop count: The number of traversed hops can be used for prioritization since losing, dropping or missing the deadline of a packet which has been traversed more hops will be waste of more network resources than the one has been traversed less hops. Therefore, giving higher priority to the packets which has been traversed more hops and lower priority to the fewer traversed ones might be a reasonable approach for utilizing the network resources and even distribution of the latency throughout the network. Moreover, relatively further sensor nodes from sink usually have smaller change to deliver their packets since they have to travel more hops and have higher chance of collision, drop or deadline missing. Speeding up the packet as it closes to the sink also provides fairness among sensor nodes in terms of successful delivery of the packets.
- Packet deadline: The more a packet is close to miss its deadline, the more priority it has since the packet will become useless if the deadline misses. By this way, waste of network resources also prevented.
- Remaining energy: Increasing the priority of the packets as the remaining energy of the owning sensor node decreases, gives the sensor node a chance to process as much packet as it can before its energy exhausted.
- Source type: Forwarding loads of the sensor nodes can change depending on their position or role (leaf node, relay node, cluster head) in the network. Giving higher priority to the sensor nodes that has relatively heavier forwarding load can decrease the packet dropping ratios caused by buffer overflow.
- Hybrid: Sensor node can determine the priority of the packet by considering more than one criteria. By giving certain weights to these parameters, a local urgency of the packet can be calculated and mapped to a priority level.

Selected priority assignment method is quite important for QoS support and need to be selected carefully. Assigning the priorities statically is not a complex issue since there is no need for any calculation. Once the priority is given, it does not change during the delivery of the packet. On the other hand, dynamic priority assignment needs some additional calculation and reassignment in each hop which brings an extra overhead to the QoS mechanism. However, adaptive changes in the importance of the packets improve the performance of the QoS mechanism.

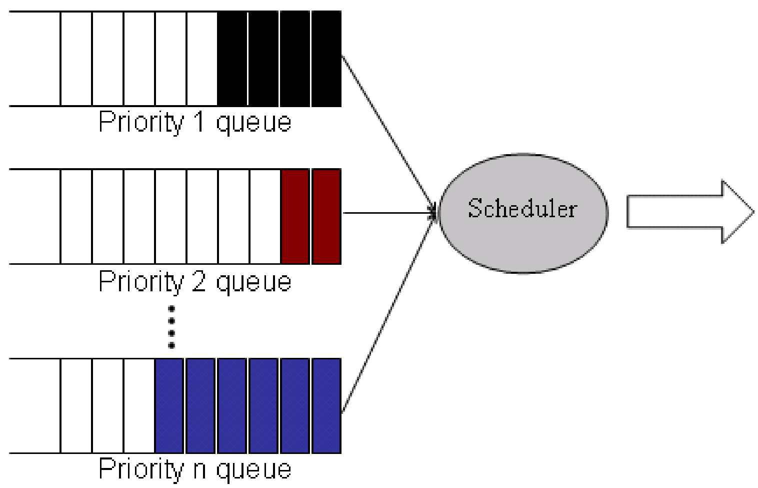
Decision parameters needed in dynamic assignment may not be present in the format of the packet so that additional data fields may be required. This causes bigger packets which means longer transmission times and energy consumption. It is enough to have a simple priority field in the header of the packet in case of static priority. Moreover, dynamic priority assignment method mostly needs decision parameters which are not MAC-specific and necessitates cross-layer mechanisms.

2.5.3. Single-queue vs. Multi-queue Architecture

Main drawback of the single-queue scheme is the high cost of managing the relatively long queue of packets as seen in Fig. 2.9(a). Since different priority packets stored in the same queue, it is impractical to keep them sorted and process the packets according to their priorities. On the other hand, multi-queue scheme chops the long single queue into pieces and constitutes smaller different priority queues as seen in Fig. 2.9(b). By this way, packets can be served with a simple FIFO fashion and additional sorting or searching operations are not needed anymore. However, multi-queue systems have to make some sacrifice from the accuracy of the prioritization if we have more priority levels than the number of available queues since all packets in the same queue treated as they all have equal priority. Moreover, in case of multi-queue systems, a fair packet scheduler must be integrated to select the next serviced queue based on the requirements of the classified traffic. If not, explicit precedence might cause intolerable performances for lower priority traffic.



(a) Single-Queue architecture



(b) Multi-Queue architecture

Figure 2.9. MAC layer queue architectures

2.5.4. Packet Scheduler

In single-queue architectures, there is no need to use a packet scheduler. However, in multi-queue architectures, a packet scheduler must be integrated to select the next serviced queue as in Fig. 2.9(b). There exists two design methods for the packet scheduler. First method is serving the higher priority queue always prior to lower priority queues explicitly. The second method is utilizing some kind of fair queueing between the different priority queues.

Main drawback of the explicit prioritization is probability of intolerable performances for lower priority traffic in terms of latency, successful packet delivery ratio, etc. However, higher priority traffic achieves relatively better performances since it always served first. Also, explicit prioritization can be chosen for the sake of simplicity since it is easy to implement and operate.

There exists many techniques for fair queueing such as weighted round robin, weighted fair queueing, deficit round robin to be used in the second method. Integrating a fair queueing mechanism brings some performance degradation for the higher priority traffic since it serves the nonempty queues based on a scheduling algorithm. Also, it is relatively more complex than the simple explicit prioritization mechanism. However, small sacrifice from performance of higher priority traffic results remarkable performance increase for lower priority traffic.

2.6. Properties of a Well-designed QoS-Aware MAC Protocol

As we mentioned earlier, the major problem in WSNs is lack of resources. Since depletion of energy makes the sensor nodes useless, energy scarcity leads the resource constraints. Therefore, designed MAC protocol must be aware of energy while providing QoS support. Also, WSNs have limited resources in terms of memory and processing capability. Hence, computationally complex and overwhelming algorithms are not feasible. Since aim of the MAC layer is coordinating the medium access and WSNs have to operate at relatively scarce bandwidths, better throughput performances need to be provided with high channel utilization.

WSNs can contain numerous sensor nodes or can be deployed to huge areas. For this reason, scalable MAC protocols are needed. Moreover, node mobility, natural disasters or node malfunctioning may result in highly dynamic network topology which makes the adaptive MAC layer requirement a must.

Priority assignment methods must be fair and accurate in order to achieve better QoS performance. Poor prioritization of the traffic leads to non-utilized network resources or waste of resources. Since WSNs are highly application-specific, the requirements need to be identified with great attention and must be used as a primary factor for design tradeoffs.

Features listed above must exist in a well-designed QoS-Aware protocol but not enough to be one. As addressed earlier, performance of the QoS-aware MAC protocols extremely depends on the requirements of the application. For example; delay intolerant real-time applications necessitate fast delivery of the data or evenly distributed latency among sources to reduce the jitter meanwhile mission critical applications require reliable communication. As a final remark, specific requirements of the application related to QoS constraints must be determined and fulfilled with great care.

3. DIFF-MAC DESIGN AND PROPERTIES

Previously proposed QoS-aware MAC protocols already defined many techniques to improve the efficiency of the QoS-provisioning. Nevertheless, they focus on some specific aspects and are far away from combining and melting these techniques into a single protocol to construct a complete solution for the MAC layer. Diff-MAC utilizes methods introduced by many previous studies in the literature and provides a fair all-in-one QoS-aware MAC protocol which is supported with an example scenario based on a security surveillance application.

In this chapter, we introduce Diff-MAC and its key features for QoS-provisioning. Diff-MAC adopts a CSMA/CA based medium access with RTS/CTS and acknowledgements and Fig. 3.1 shows the simplified state transition diagram for the operation of the protocol. Sensor nodes adopt a sleep-listen schedule to conserve energy and each node follows its own independent schedule, so that Diff-MAC does not require any synchronization between the neighboring sensor nodes. Diff-MAC manages the sharing of the medium by adapting various parameters according to the requirements of the flowing traffic in the network which are explained in the following sections.

3.1. Fragmentation & Message Passing

Created video frames are relatively long messages and transmitting them as a single packet is too costly especially in case of MAC failures where retransmissions are required. Diff-MAC fragments the long video frames into smaller video packets and transmits them as a burst. Traditional RTS-CTS-DATA-ACK mechanism is used in Diff-MAC and once the medium is reserved, all packets of the corresponding video frame are sent as a burst using a mechanism similar to the message passing feature of the SMAC protocol [11] as shown in Fig. 3.1. In order to accurately obtain and give meaning to the packets of the relevant video frame, a field called “packet in frame” is added to the packet structure. This field is used at the receiver side to assure consistency of the video frame. Moreover, neighboring sensor nodes around the source and destination pair enter into sleep state during a video frame exchange after receiving the RTS-CTS packets which in turn provides considerable amount of energy saving.

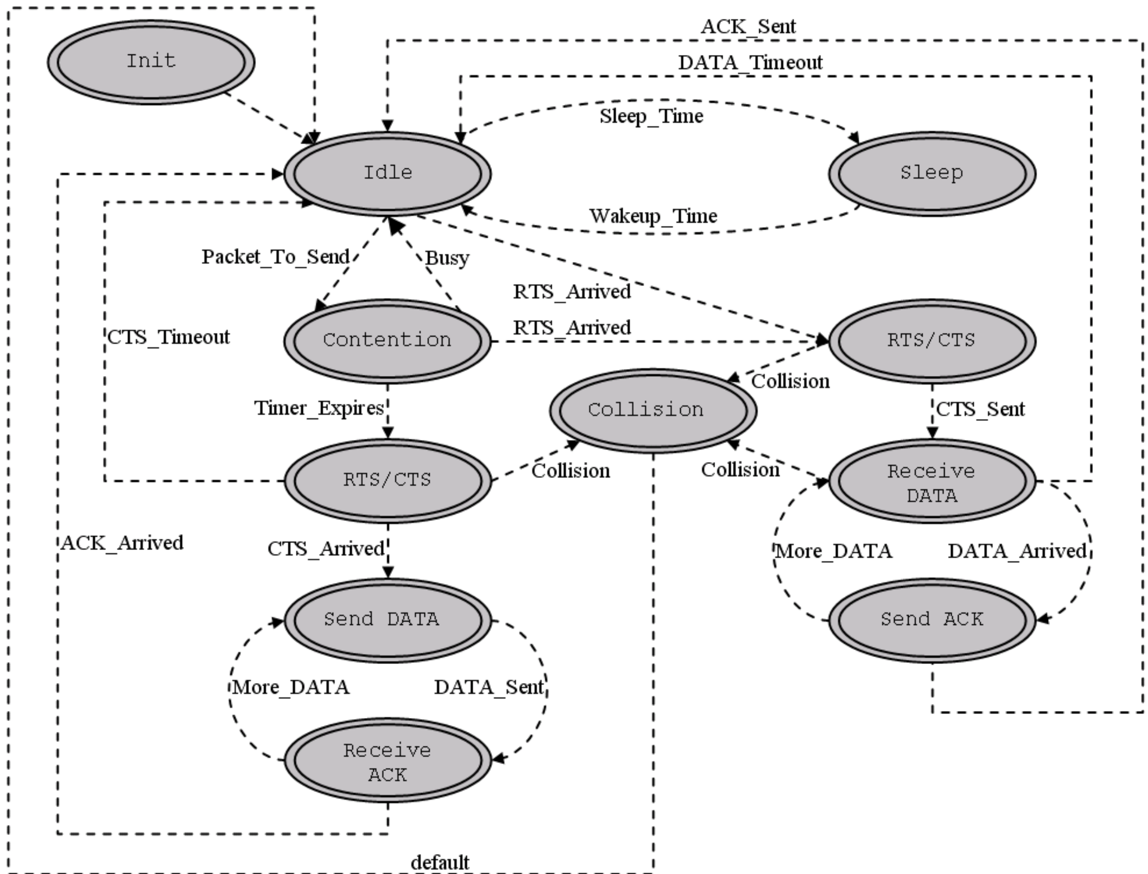


Figure 3.1. Simplified state transition diagram of Diff-MAC

3.2. Contention Window Size Adaptation

The objective of this mechanism is to reduce the number of collisions and keep the CW size as small as possible in order to avoid unnecessary waiting time to reserve the medium by adjusting the current CW size of the sensor node based on the dynamic network traffic conditions.

In order to adjust the CW size adaptively, Diff-MAC periodically monitors the behavior of the network, with period (T_c), and collects two related metrics about the current state of the network which are total number of transmission attempts (A_t) and the number of collisions (A_c). Accordingly, a probability of collision (P_c) value can be computed for that observation frame. This obtained probability of collision then is used as an input for the CW adaptation algorithm and calculated by $P_c = \frac{A_c}{A_t}$.

As seen in the algorithm given in Fig. 3.2, adaptation mechanism varies the current CW sizes corresponding to each traffic class between the maximum and the minimum values step-by-step. Diff-MAC runs the CW adaptation routine if and only if more than a certain number of transmission attempts (ϱ) have been done during (T_c). Therefore, redundant and inaccurate adjustments are prevented.

1: $CW_{cur} = (CW_{min} + CW_{max})/2$
2: `Observe transmission attempts` (A_t) `during` (T_c)
3: `if` $(A_t) < \varrho$
4:     `go to Step 2`
5: `if` $P_{c(t)} < P_{c(t-1)}$
6:     $\Delta CW = \alpha_{down}(CW_{min} - CW_{cur})$
7: `else`
8:     $\Delta CW = \alpha_{up}(CW_{max} - CW_{cur})$
9: $CW = CW_{cur} + \Delta CW$
10: `go to Step 2`

Figure 3.2. CW adaptation algorithm for a given traffic class

For service differentiation, two methods are utilized. The first method is setting the speed of the CW adaptation based on the traffic type by controlling the adaptation coefficients. Diff-MAC increases the CW size faster for lower priority traffic while decreases faster for higher priority traffic which means $\alpha_{up(RT)} < \alpha_{up(NRT)} < \alpha_{up(BE)}$ and $\alpha_{down(RT)} > \alpha_{down(NRT)} > \alpha_{down(BE)}$ where α represents the adaptation coefficient. Moreover, different up&down coefficients are used for the same priority traffic like $\alpha_{up(RT)} < \alpha_{down(RT)}$ and $\alpha_{up(BE)} > \alpha_{down(BE)}$ in order to decrease latencies of the delay-intolerant RT data. Therefore, the CW size of the RT class decreases sharper than it increases. A similar CW adaptation mechanism utilized by Saxena et al. [7] in a stop-for-a-round fashion. Saxena et al. MAC waits for other sensor nodes to adjust their CW sizes. In other words, to change the current size of the CW, increased CW size must be followed by a decreased collision rate or decreased CW size must be followed by a increased collision rate. On the other hand, adaptation mechanism of Diff-MAC continuously adapts the CW size regardless of the neighboring sensor nodes, hence achieves more accurate CW sizes faster than Saxena et al. MAC. The second method is setting different maximum and minimum CW sizes for each traffic class, hence giving different priorities for reserving the medium. To increase the throughput and decrease the latency of the higher priority traffic, we set $CW_{RT} < CW_{NRT} < CW_{BE}$ where CW is the size of the CW and give precedence to higher priority traffic. Since we use non-overlapping CW, this statement holds for both minimum and maximum CW sizes.

Although Diff-MAC dynamically adapts the CW size to the current network conditions, the minimum and the maximum CW sizes of the traffic classes have to be selected carefully. The packet traffic modeling for intrusion detection derived by Demirkol et al. [18] can be extended for video sensor networks. For each sensor node deployed, the probability of that node to be within the depth of field (DoF)-distance of the point is a Bernoulli trial, where the probability of success is $\frac{\pi(DoF)^2}{LW}$ where (L, W) is the length and with of the surveillance area. Since a sensor node covers camera observation angle (COA) of 360 degrees, we can also say the probability of covering the point is again a Bernoulli trial where the probability of success is $\frac{COA}{360}\frac{\pi(DoF)^2}{LW}$. Hence, the number of video sensor nodes within distance DoF of a point and oriented to that point forms a Binomial distribution and for large number of sensor nodes this distribution can be represented by a Poisson process with mean value of $\frac{N\pi(COA)(DoF)^2}{360LW}$ where N is the number sensor nodes deployed to the surveillance area. In [19], the energy optimizing and the delay optimizing CW sizes are derived as a function of the number of contending nodes. Since we know the average number of contending sensor nodes and the optimum CW size as a function of the number of contending nodes, we can further calculate the CW sizes of the Diff-MAC by combining the techniques described in [18] and [19]. However, [18] and [19] make analysis of the single class case and gives us a rough idea about the CW sizes of our each traffic class.

3.3. Dynamic Duty Cycling

Aim of this mechanism is to reduce both packet latencies and idle listening. Similar to the CW adaptation mechanism, Diff-MAC observes the total number of processed packets (created, received or relayed) every T_d seconds and classifies them based on their belonging traffic classes. After the classification, Diff-MAC sets the active time of the sensor node according to the currently dominating traffic class to refrain from both idle waiting time caused by the sleeping next hops and unnecessary waste of energy caused by idle listening. Every traffic class has a corresponding active time where $TA_{BE} < TA_{NRT} < TA_{RT}$ and Diff-MAC directly adjusts the listen duration of the sensor nodes. Consequently, the node which dominantly processing RT data i.e. source and the relay nodes between the detection area and the sink stays awake longer and provides fast delivery of the video data. If the total number of processed packets is smaller than a certain threshold (δ), the active time of the sensor node set to the smallest level since the traffic on the node is negligible. However, Diff-MAC does not provide any synchronization between the neighboring sensor nodes and each node follows its own independent sleep-listen schedule.

3.4. Intra-node & Intra-queue Prioritization

There is a tradeoff in the operation of multi-queue and single-queue QoS-aware MAC protocols. Main drawback of the single-queue scheme is the high cost of managing the relatively long queue of packets. Since different priority packets are stored in the same queue, it is impractical to keep them sorted and process the packets according to their priorities. On the other hand, multi-queue scheme chops the long single queue into pieces and constitutes smaller different priority queues. Thus, packets can be served with a simple FIFO fashion and additional sorting or searching operations are not needed anymore. However, multi-queue systems have to tradeoff the accuracy of prioritization if we have more priority levels than the available queues since all packets in the same queue treated as they all have equal priority. Moreover, in the case of multi-queue systems, a fair packet scheduler must be integrated to the MAC protocol to select the next serviced queue based on the requirements of the classified traffic. If not, explicit precedence might cause the lower priority traffic to starve and suffer from intolerable performance.

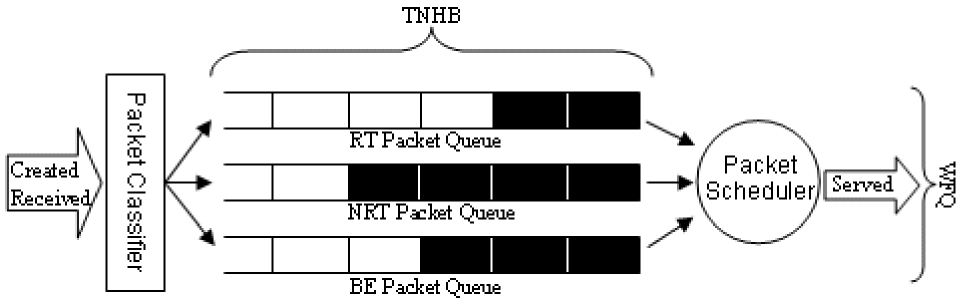


Figure 3.3. Multi-queue architecture of Diff-MAC

In order to fulfill the requirements of the QoS-constrained traffic and provide fairness among all nodes in the network, priority assignment methods become more important. Priorities can be assigned in a static, dynamic or hybrid manner. Static priority assignment is rather simple and easy to implement. However, statically assigned priorities might have problems to adapt to the changes in the network conditions. On the other hand, dynamic priority assignment methods take the current network conditions into consideration and mostly require some additional information and operations to decide on the priority. Hybrid methods utilize both static and dynamic assignment methods and determine the priority of a packet based on several criteria.

Diff-MAC comprises three different priority packet queues for each traffic class as depicted in Fig. 3.3. As we mentioned, in multi-queue systems, efficient scheduling mechanisms are needed to provide fairness among different priority traffic and to bound the worst case performances. Most of the proposed protocols employ explicit prioritization and serve higher priority queues always first since this sharing model is easy to implement. In this work, we utilize packetized Weighted Fair Queuing (WFQ) method [66] where each queue has its own weight. Packet scheduler of the Diff-MAC selects the next serviced packet based on weights of the queues. With WFQ, the medium sharing rates among the traffic classes can be adjusted easily by changing the corresponding queue weights. This brings the ability of controlling the medium access, hence relative throughput of each traffic class. Moreover, increase in the diversity of the traffic at the contending sensor nodes reduces the collisions since each traffic class uses different CW sizes.

Majority of the queuing systems use a FIFO model to manage and determine the next packet to be processed. However, resource constrained nodes may lack memory to allocate separate queues for each priority or there might be excessively too many priority levels. Hence, group of packets belonging to similar priority levels have to be stored in the same queue. Because of this, some additional intra-queue management mechanisms can be adopted for better network performance at the expense of keeping the queues sorted.

In order to provide more precise prioritization, Diff-MAC assigns the priorities of the packets based on their traversed hop count in a dynamic manner which is named as Traversed Number of Hops Based Prioritization (TNHBP). TNHBP gives precedence to the packets for which more energy, bandwidth, memory and time have already been allocated. Since dropping these packets will be more costly, TNHBP prevents waste of network resources by relaying them to the next hop immediately. Therefore, Diff-MAC provides a two-level hybrid prioritization scheme, first being the type of traffic class and second being the traversed hop count among the packets of the same traffic class. TNHBP keeps the packet queues sorted according to the traversed hop counts rather than searching the whole queue for finding the highest priority packet. Therefore, TNHBP requires a search operation with a worst and average case complexity $O(\log n)$ to find an index for a new packet and a shift operation to free space prior to insertion. With the integration of TNHBP, Diff-MAC drops the packets already queued for a longer time, i.e. closer to miss a deadline, among the same priority packets, rather than dropping the newly created or received packets.

4. PERFORMANCE EVALUATION OF DIFF-MAC

4.1. Scenario

Since the effect of the employed protocol on the overall performance of the network is highly application dependent, we set up an example scenario which is suitable for WMSNs. Although various other application fields can be found, our main theme will be security surveillance for which the primary concern is always fast and reliable delivery of the created video data related to the observed phenomena. That is why, video frames will be the first traffic class carried by our network and will be given the highest priority. In order to accurately detect and eliminate the threats, we also collect non-visual information about the area under observation like temperature, radioactivity, sound, light, vibration or pressure which is given the second priority. This kind of scalar information can be varied up to the capabilities of the sensor nodes since a single packet would be enough to store all of them. As the third traffic class, auxiliary control packets are carried by the network including the location information of the sensor node, remaining energy, current operation parameters like camera observation angle (COA), image quality, orientation angle. As a result, we have three traffic classes which are real-time (RT), non-real-time (NRT), best effort (BE) in order with their priorities and this scenario will also be our basis for performance evaluation of Diff-MAC.

Since continuous video frame generation from all sensor nodes will be a waste of critical resources, target detection mechanism is used to trigger the video streaming. As shown in Fig. 4.1, a sensor node creates video frames during the target is moving between the points A and B. The time spent between A and B called the dwell time and can be calculated as $T_{dwell} = \frac{d_{AB}}{\overrightarrow{V}}$ where d_{AB} is the distance of $|AB|$ and $\overrightarrow{V}$ is the velocity of the target. Thus, a camera working with K frames per second (fps) creates a video stream of $K.T_{dwell}$ frames in case of an intrusion.

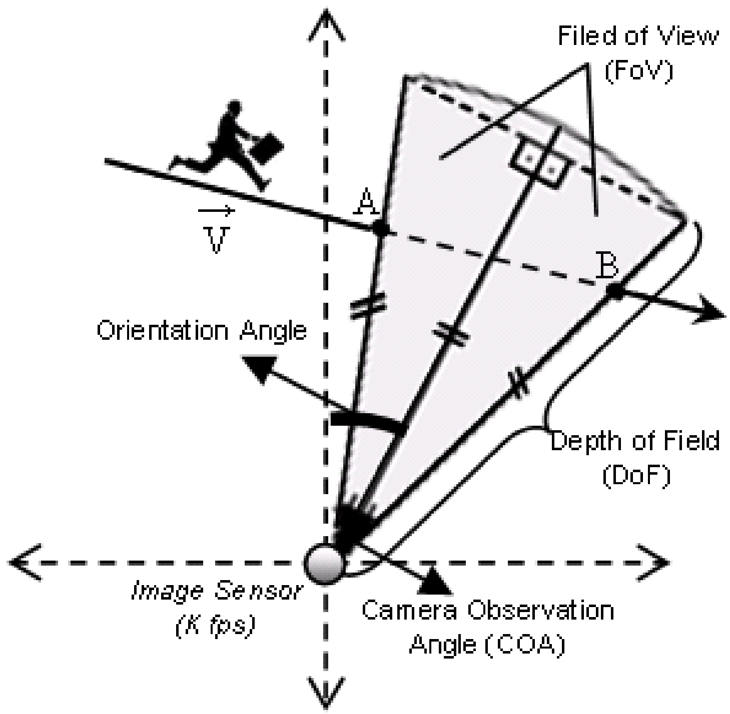


Figure 4.1. Camera detection model

4.2. System Model and Simulation Parameters

For the performance evaluation of our protocol, each case is simulated 10 times with different seeds using the OPNET [21] modeler environment. Test cases are 30-minutes long and the first 5 minutes of the simulation regarded as warm-up period since stabilization of the network may take couple of minutes. That's why, results obtained during the warm-up period discarded. In compliance with our broad scenario introduced in Section 4.1, we have a square shape surveillance area and a single sink deployed to the lower left corner of this area for forwarding the gathered information to a safe zone. Deployed sensor nodes are equipped with a camera [53] and have the ability to compress the produced video in the form of sequence of images. We assumed Sub Quarter Common Intermediate Format (SQCIF) which has a resolution of 128x96 since it has a lower complexity relative to other proper alternatives. Although distributed source coding techniques are promising alternatives for encoding video in WMSNs [50], a stable practical implementation has not been proposed yet. That's why, we used JPEG compression which is available on the image module of the sensor nodes. Quality of the produced video can be controlled by changing the created image frames per second (fps) and accuracy of the scalar data can be controlled by changing the packet interarrival times. Different types of traffic loads offered to the network can be found in Table 4.1.

Table 4.1. Offered Traffic Load Types

	Frame Rate RT (fps)	**Interarrival Time NRT & BE (sec)**	**Average Created Traffic (Pkt/Sec)**
Type 1	2	12	23.14
Type 2	4	10	31.65
Type 3	6	8	43.96
Type 4	8	6	58.12
Type 5	10	4	83.25
Type 6	12	2	139.32

In our simulations, each video frame has a size of 10 Kbits which will be fragmented into 1 Kbits-long video packets. NRT and BE packets are 200 bits long and packet interarrival times are poisson distributed. The target is assumed to be a pedestrian which moves in the surveillance area according to the Random Waypoint Mobility [20] model and its velocity is constant 1 m/s. We applied the binary detection model where the target is sensed with the probability of 1 when it is within the FoV of the sensor node as seen in Fig. 4.1.

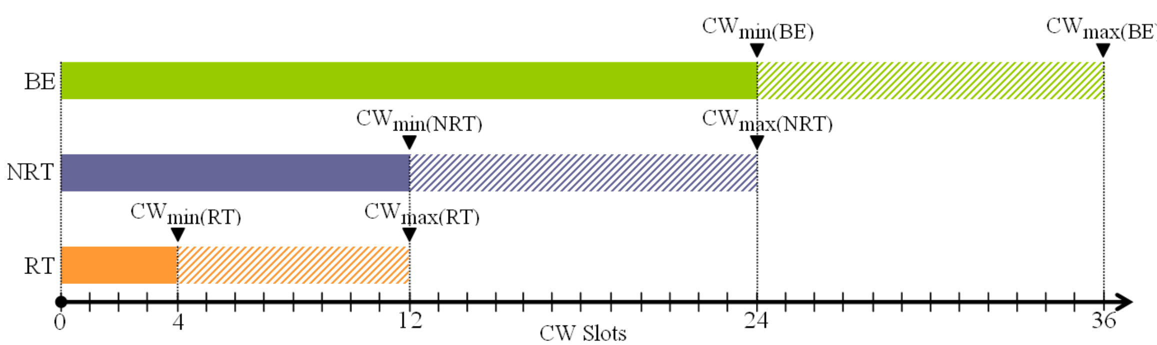


Figure 4.2. Minimum and maximum contention window sizes for each traffic class

With the help of two methods [18, 19] mentioned in Section 3.2; minimum CW sizes of the RT, NRT and BE traffic used as $CW_{min(RT)} = 4, CW_{min(NRT)} = 12, CW_{min(BE)} = 24$ where the maximum CW sizes are $CW_{max(RT)} = 12, CW_{max(NRT)} = 24, CW_{max(BE)} = 36$ respectively. Fig. 4.2 shows the minimum and maximum CW sizes of each traffic

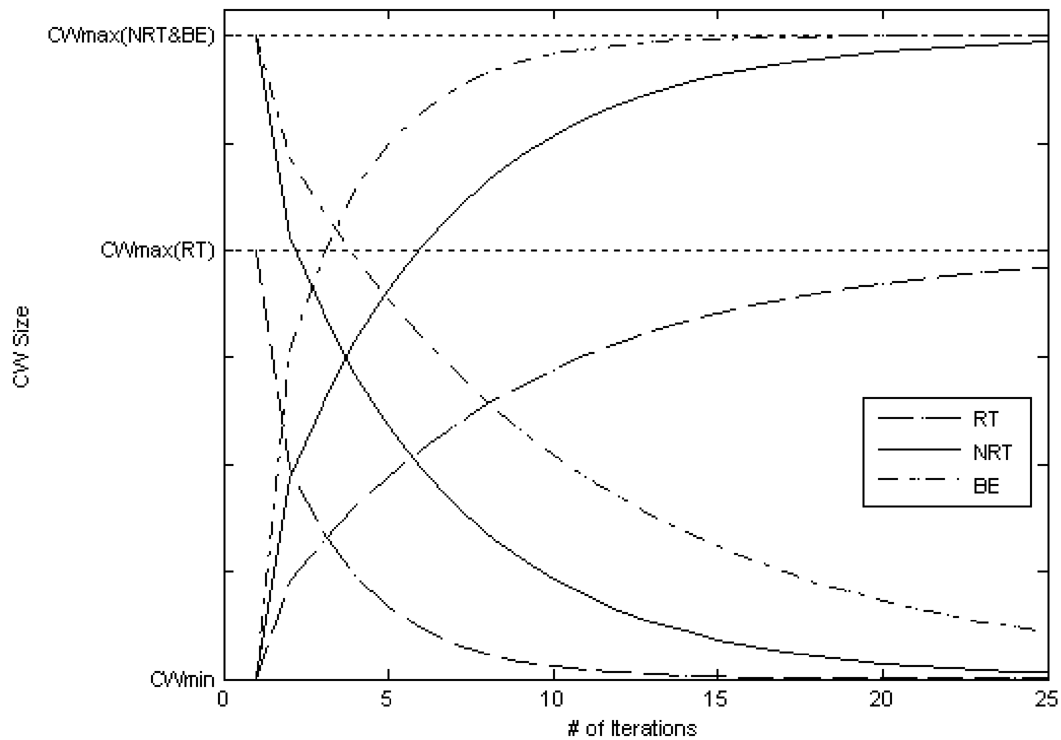


Figure 4.3. Effect of adaptation coefficients (α_{up} and α_{down}) on the convergence of CW sizes for each traffic class

class. The current CW size (CW_{cur}) of a particular traffic class can vary between the respective minimum and maximum CW sizes which is indicated by the striped portion of the CW bars in Fig. 4.2. Respective adaptation coefficients are $\alpha_{up(RT)} = 0.12, \alpha_{up(NRT)} = 0.17, \alpha_{up(BE)} = 0.3$ for increment and $\alpha_{down(RT)} = 0.3, \alpha_{down(NRT)} = 0.17, \alpha_{down(BE)} = 0.1$ for decrement.

As seen in Fig. 4.3 which is a result of CW adaptation algorithm given in Fig. 3.2 in Section 3.2, the CW size of the higher priority traffic decreases faster and increases slower than lower priority traffic. Moreover, the CW size of the higher priority traffic decreases faster than it increases and the CW size of the lower priority traffic increases faster than it decreases. Selected DC for dominating RT, NRT and BE traffic are 95%, 60% and 40% respectively which equals $TA_{RT} = 95msec$,$TA_{NRT} = 60msec$ and $TA_{BE} = 40msec$. Although these values seem to be high at first sight, we must remember that our sensor nodes are operating in a heterogeneous WMSN and deliver QoS constrained real-time traffic. Keeping DC of the sensor nodes too low causes an incapable sensor network which cannot fulfill the application requirements because of the low transmission rates of the sensor devices. The energy consumption values for transmission, reception, idle and sleep states are 27 mJ, 10 mJ, 10 mJ and 1 μJ respectively in compliance with the Xbow Mica mote products [61]. Network layer is handled by GPSR [22] and crucial parameters used in our simulations are listed in Table 4.2.

Table 4.2. Simulation Parameters

Parameter	**Value**
Surveillance Area	$400 \times 400 m^2$
Network Size	100 Nodes
Deployment Type	Uniform Random
Video Frame Size	10 Kbits
Video/Scalar Packet Size	1 Kbits/200 Bits
Camera Frame Rate	2 to 14 fps
Camera Observation Angle	52 deg.
Depth of Field	30m
Bandwidth	250 Kbps
Video/Scalar Buffer Size	50 Kbits/4 Kbits
Target Mobility Model	Random Waypoint
Target Velocity	1 m/s
Routing Algorithm	GPSR
# of Runs	10
# of Targets	1
Detection Model	Binary FoV
Communication Range	80m
Queue Weights (RT/NRT/BE)	0.7/0.2/0.1

In our simulations, we assumed perfect-reception-within-range model for the sake of simplicity. In other words, a particular sensor node can perfectly exchange packets with the neighboring sensor nodes within its communication range. However, real life applications are far away from this assumption and realistic link layer models need to be utilized. Channel conditions and radio capabilities must be considered especially in large sensor networks since the overall performance of the network can be highly effected. Therefore, we used a realistic link layer model proposed in [67] for hop-based performance evaluation of Diff-MAC. Zuniga et al. use mathematical techniques from communication theory to model and analyze low power wireless links. They consider important channel and radio parameters such as the path loss exponent and shadowing variance of the channel; and the modulation and encoding of the radio. In their work, log-normal shadowing path loss model [68] used as radio propagation model and given by:

$$PL(d) = PL(d_0) + 10nlog_{10}(d/d_0) + X_\sigma \tag{4.1}$$

Where d is the distance between the transmitter-receiver, d_0 a reference distance, n the path loss exponent, and X_σ a zero-mean Gaussian random variable with standard deviation σ ($N(0, \sigma)$). n used for the rate at which signal decays along its path and σ used for the shadowing effects. The received signal strength (P_r) at a distance d is the difference between the output power of the transmitter (P_t) and $PL(d)$ which is given in (4.2).

$$P_r = P_t - PL(d) \tag{4.2}$$

X_σ is a random process that is a function of time and hence, the received signal strength may change with the time even for the same distance and transmitter output power. MICA2 [61] motes use the Chipcon CC1000 radio [62], which has a noise figure of 13 dB and a system noise bandwidth of 30 kHz. Assuming an ambient temperature of 27 °C and no interference, the noise floor (P_n) is -105 dBm. Then, signal-to-noise-ratio (SNR) at a distance d is received signal strength minus the noise floor and given in (4.3).

$$SNR(d)_{dB} = P_{r\ dB} - P_{n\ dB} \tag{4.3}$$

In [69], authors observed the wireless channel features and performed measurements in the 800-1000 MHz band. They choose eleven locations to measure the channel behavior such as apartment hallway, one-sided corridor, flat beach, bamboo, dry tall underbrush. Since we are interested in security surveillance as introduced in Section 4.1, “dry tall underbrush” is the most suitable site among their measurement locations which is told to be tall grassy fields with few tall bushes. Although their results lie in a large interval, they also provide the mean of their measurements and we used $n = 3.6$, $\sigma = 8.4\, dB$, $d_0 = 1m$ and $PL(d_0) = 34.8$ for our simulations.

Assuming non-return-to-zero (NRZ) encoding where 1 Baud = 1 bit and non-coherent frequency shift keying (FSK) modulation scheme for the radio model similar to MICA2 motes, probability of successfully receiving a packet (PSR) $p(d)$ at a distance d is:

$$p(d) = (1 - \frac{1}{2}\, exp^{-\frac{SNR(d)}{2}\frac{1}{0.64}})^{8f} \tag{4.4}$$

Where f is the packet size in bytes. Fig. 4.4 obtained through equation 4.4 and shows how analytical PSR changes with distance. As seen in the Fig. 4.4, we can divide a wireless link into three distinct reception regions: connected, transitional, and disconnected. In the connected region, mostly perfect packet reception occurs while in the disconnected region, mostly zero packet reception occurs. Transitional region is an intermediate region between the connected and the disconnected regions, and mostly represents unreliable links. Zuniga et al. also derive mathematical expressions to calculate the bounds of this transitional region regarding both the channel and radio conditions.

However, integrating the calculation-intense realistic link model to the simulation tool results in very long execution times. Therefore, we used this model only in the hop-based performance evaluation of Diff-MAC in which the effect of the link layer comes into prominence. Perfect-reception-within-range model assumed for the rest of our simulations.

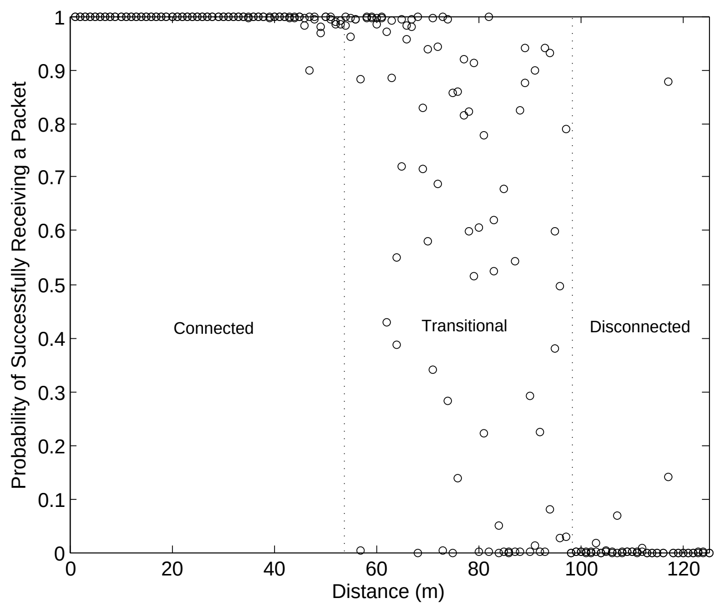


Figure 4.4. Analytical probability of successfully receiving a packet vs. distance where $n = 3.6$, $\sigma = 8.4\ dB$, $d_0 = 1m$, $PL(d_0) = 34.8\ dB$, $P_n = -105\ dBm$, and $P_t = 5\ dBm$

A packet can be one of the two modes in GPSR: perimeter mode and greedy mode. All packets are created in the greedy mode by default. If the sensor node has a geographically nearer neighbor to the sink, the nearest neighbor is assigned as the next hop and a data gathering tree is constructed as seen in Fig. 4.5. If the sensor node is the closest one to the sink among its neighbors, that sensor node is called a “local minimum” and relayed packets at the local minimum are entered to the perimeter mode. Perimeter mode packets are forwarded based on the right-hand rule and a reduced connectivity graph called Relative Neighborhood Graph (RNG) used as an

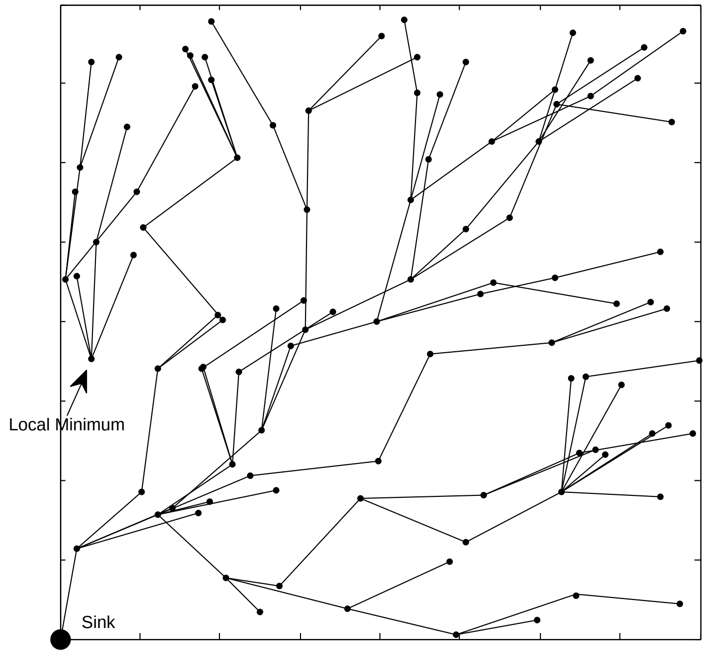


Figure 4.5. Sample data gathering tree constructed by GPSR based on Greedy Forwarding

input to that rule which can be seen in Fig. 4.6.

A sample data gathering tree constructed by GPSR is depicted in Fig. 4.5. There is a local minimum in the left-center of the surveillance area caused by the random deployment of the sensor nodes. When a packet created or received to be relayed by a local minimum, packet enters the perimeter mode and next hop is determined based on the right-hand rule by using the RNG graph shown in Fig. 4.6. When packet is forwarded to a sensor node which is closer to the sink than the sensor node it enters perimeter mode, packet reenters the greedy mode again and continues to be routed greedily.

Video coverage of the WMSNs are constructed by FoV (Field of View) areas which is formed by DoF (Depth of Field) and COA (Camera Observation Angle) as seen in Fig. 4.1. In our simulations, we used DoF as 30m and COA as 52 degrees. Target detection occurs when the target is within the FoV of the any sensor node and

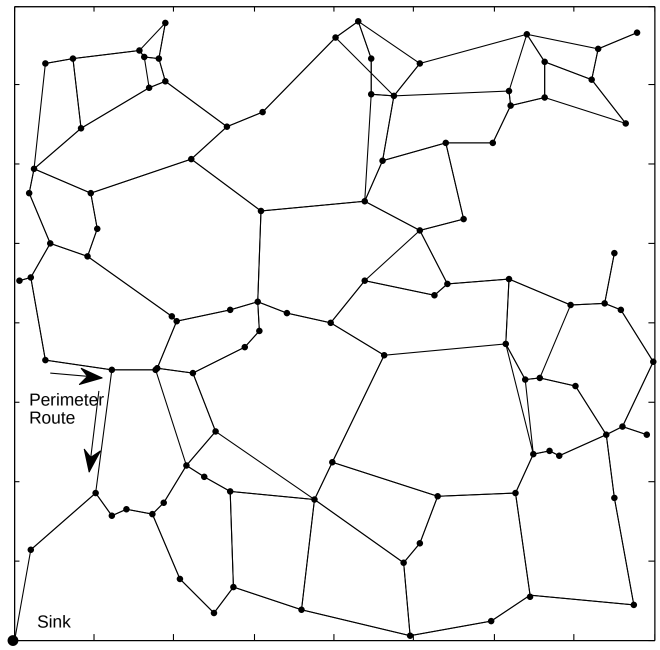


Figure 4.6. Sample RNG graph constructed by GPSR

a sample resulting video coverage of our network is depicted in Fig. 4.7. The dotted rectangle represents the actual surveillance area and seems to be sparsely covered. However, it is impossible for a trepasser to cross over the surveillance area without being notified by any of the sensor nodes. A couple of sensor nodes can be seen in Fig. 4.7 which are oriented out of the observation field since we randomly deploy the camera orientations of the sensor nodes as well as their positions. Therefore, a similar mechanism introduced in [63] or [64] can be adopted to reduce the overlapping FoV areas of the sensor nodes by rotating the camera orientations to maximize the video coverage of the network.

4.3. Simulation and Performance Evaluation

Performance of Diff-MAC is evaluated with extensive simulations and compared with Saxena et al. MAC [7] and SMAC [11] protocols. We select SMAC as a competitor for our protocol since it is a basic and well known MAC protocol for WSNs and Saxena et al. MAC is the closest protocol in the literature to our protocol.

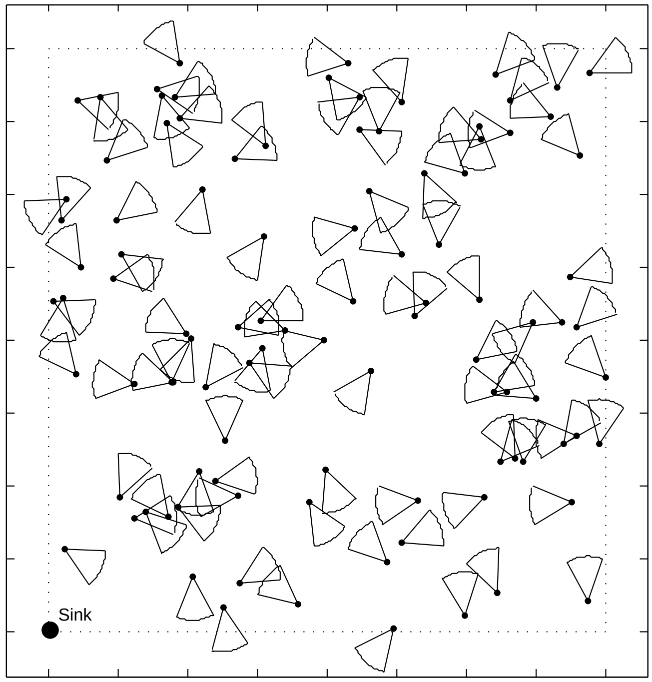


Figure 4.7. Sample surveillance area coverage

In order to make a fair comparison between the protocols, we have to make a preliminary performance evaluation of SMAC. Performance of the SMAC is highly depends on the used duty cycle (DC) because active time of the sensor nodes effects both throughput and energy consumption of the network. Therefore, we employed three different DC to find an optimum for the SMAC to be used in the remaining part of the performance evaluation.

As the active time of the sensor nodes increases, i.e. uses higher DCs, we expect the received packet rate at the sink to be increased. Fig. 4.8 depicts the comparative successful packet delivery rate of SMAC for 10%, 50%, 90% DCs with Diff-MAC. SMAC with 10% DC results in very poor packet delivery rates and does not change as the offered traffic increases since sensor nodes stay awake in a very limited portion of the cycle. SMAC with 50% DC achieves better performance than SMAC with 10% DC but worse than Diff-MAC. SMAC with 90% DC obtains satisfying results by successfully delivering most of the created packets to sink.

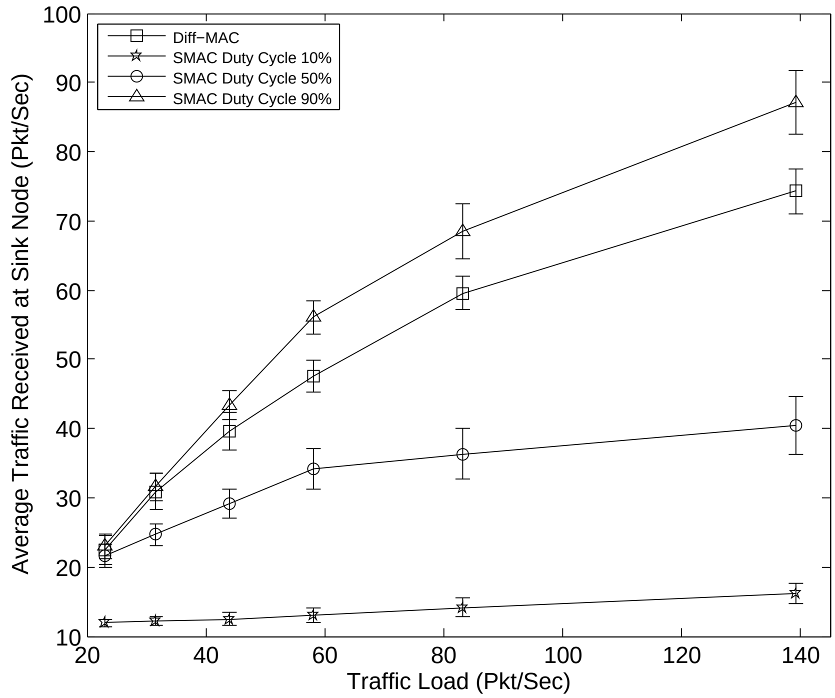


Figure 4.8. Effect of duty cycle on the successful packet delivery rate

On the other hand, we need to evaluate the energy consumption of the SMAC for each DC in conjunction with the successful packet delivery rate. Fig. 4.9 shows comparative average energy consumption of SMAC for 10%, 50%, 90% DCs with Diff-MAC. Similar to successful packet delivery rate results, average energy consumption of SMAC with 10% DC does not change so much with the increasing traffic load and outperforms all of its competitors. However, when we consider the packet delivery rate of SMAC with 10% DC, it seems to be impractical to use it. SMAC with 50% DC consumes more energy than Diff-MAC for the lightly loaded network conditions whereas consumes less energy for the heavily loaded conditions since Diff-MAC tries to adapt to the dynamic network conditions. SMAC with 90% DC is the top most energy consumer since it utilizes high active times. Moreover, the gap between Diff-MAC closes up as the traffic load increases which is another indicator of the DC adaptation of Diff-MAC. After examining Fig. 4.8 and Fig. 4.9, we determined to use SMAC 50% DC for the remaining performance evaluations. Moreover, if we recall the corresponding DCs of Diff-MAC for RT, NRT and BE traffic which are 95%, 60% and 40%, it would be irreverent to use SMAC 10% DC or SMAC 90% DC as a competitor.

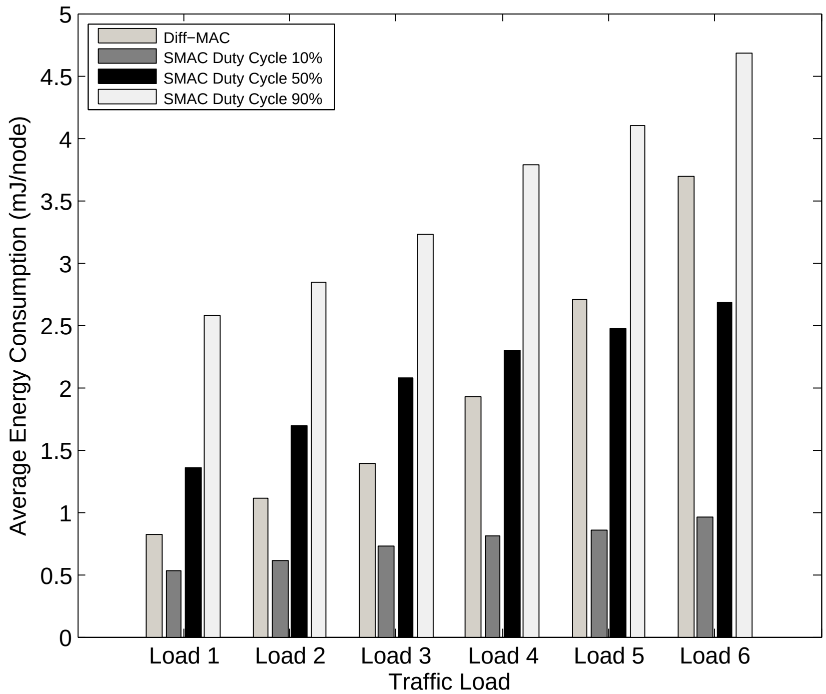


Figure 4.9. Effect of duty cycle on the average energy consumption

Fig. 4.10 presents the successfully received traffic rate at the sink node for each MAC protocol. We measure the average traffic received at the sink node for variable traffic loads given in Table 4.1. All protocols achieve nearly the same traffic delivery rate for the lightly loaded cases since most of the created packets successfully delivered. However, Diff-MAC achieves higher throughput and outperforms both its competitors as the offered traffic load increases since Diff-MAC provides higher channel utilization by integrating effective adaptation mechanisms. Moreover, fragmentation and message passing feature of the Diff-MAC reduces the retransmission costs and results in higher throughput consequently. Confidence intervals are included in Fig. 4.10 for assuring the sufficiency of the number of simulation repetitions and will not be given in the rest of the graphs.

Fast delivery of the produced traffic from sensor nodes to sink node is always one of the primary goals of the MAC layer protocols and becomes a compulsion in case of real-time or critical data. Fig. 4.11 depicts the average source-to-sink latencies of each traffic class. As seen in Fig. 4.11, Diff-MAC and Saxena et al. MAC prioritize the

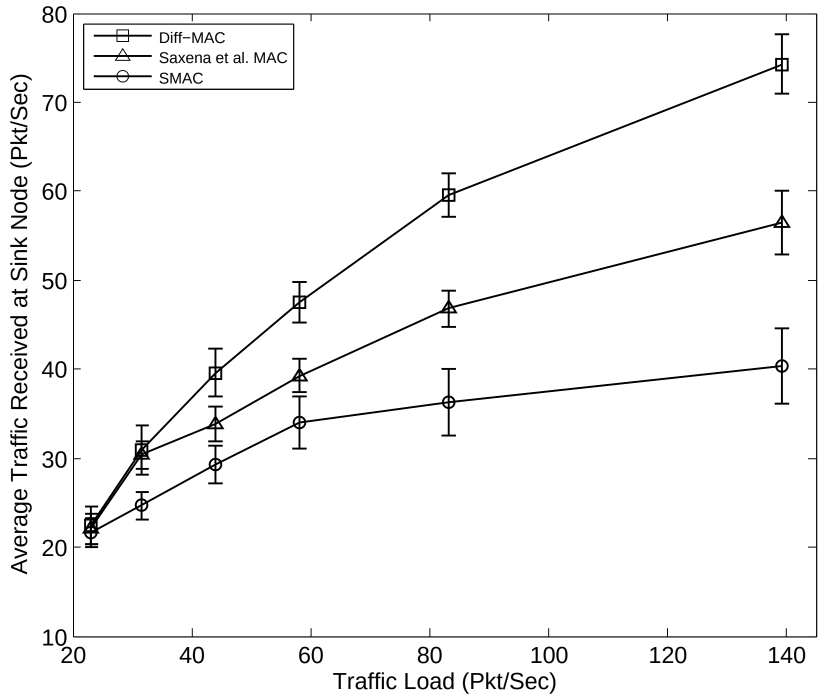


Figure 4.10. Comparative successful packet delivery rate

traffic successfully and deliver high priority traffic with low latencies. However, Diff-MAC achieves lower end-to-end latencies for each traffic class and provides fast delivery of the data with respect to Saxena et al. MAC. As the offered traffic load increases, latency performance of Saxena et al. MAC worsens and yields to intolerable delays for BE traffic. Although SMAC achieves reasonable packet latencies without any service differentiation, we must recall from Fig. 4.10 that comparative packet delivery ratio of SMAC is very low. However, used routing algorithm may severely effect the source-to-sink delay of the traffic. That's why, buffer delay of the protocols also examined and depicted in Fig. 4.12 for pure latency performance evaluation of the derived MAC layer. Diff-MAC processes the received packets rapidly and exposes lower queueing delay for each traffic class than Saxena et al. MAC. Therefore, source-to-sink latency of the packets also decreases since MAC latency is added in every traversed hop. Similar to source-to-sink latency, Saxena et al. MAC results intolerable queueing delays for lower priority traffic. The latency deviations of SMAC for increasing traffic loads relatively small because of high packet drop ratios caused by the single-queue architecture.

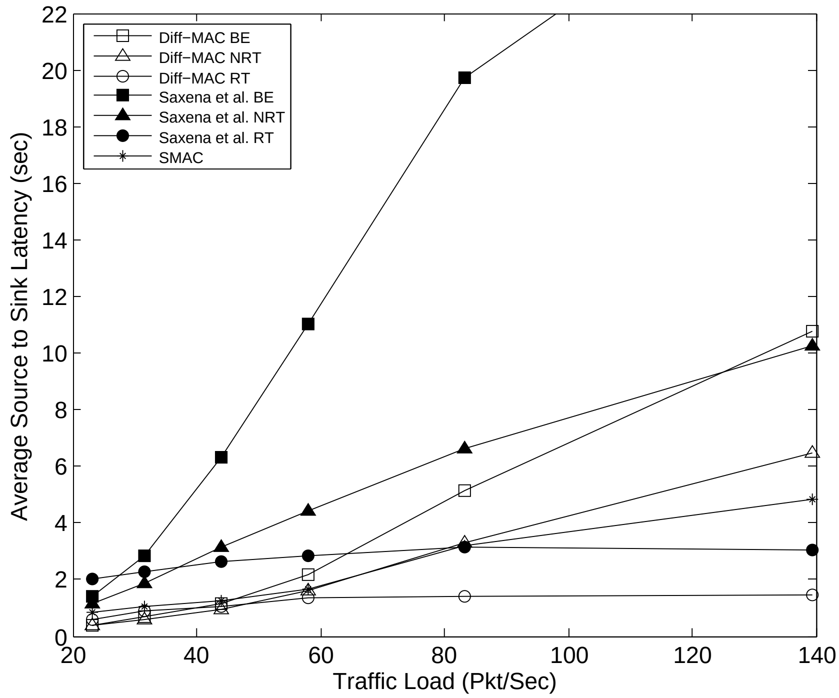


Figure 4.11. Comparative source to sink packet delay

Fig. 4.13 depicts the comparative energy consumption of the protocols for increasing traffic loads. Diff-MAC consumes less energy than both its competitors in the lightly loaded conditions whereas consumes more in the heavily loaded conditions. Because of the novel features of the Diff-MAC explained in Chapter 3, Diff-MAC reduces the active time of the sensor nodes when there is not any considerable traffic flow and similarly increases the active time of the sensor nodes when the offered traffic load is high. By this way, Diff-MAC provides a quite significant energy saving in lower traffic conditions while consumes slightly more energy to successful deliver the offered load in higher traffic conditions. Hence, we can say that the adaptivity of Diff-MAC to the current network conditions is more accurate than Saxena et al. MAC. The energy consumption variation of SMAC is lower since it utilizes a fixed DC of 50% regardless of the dynamic network conditions and does not utilize any adaptation mechanism. Fig. 4.14 shows the comparative energy consumption of the protocols per successfully received packet at the sink node. Diff-MAC consumes less energy than half of SMAC for lightly loaded traffic conditions per successfully received packet. However, the gap between Diff-MAC and SMAC closes as the traffic load increases. Energy

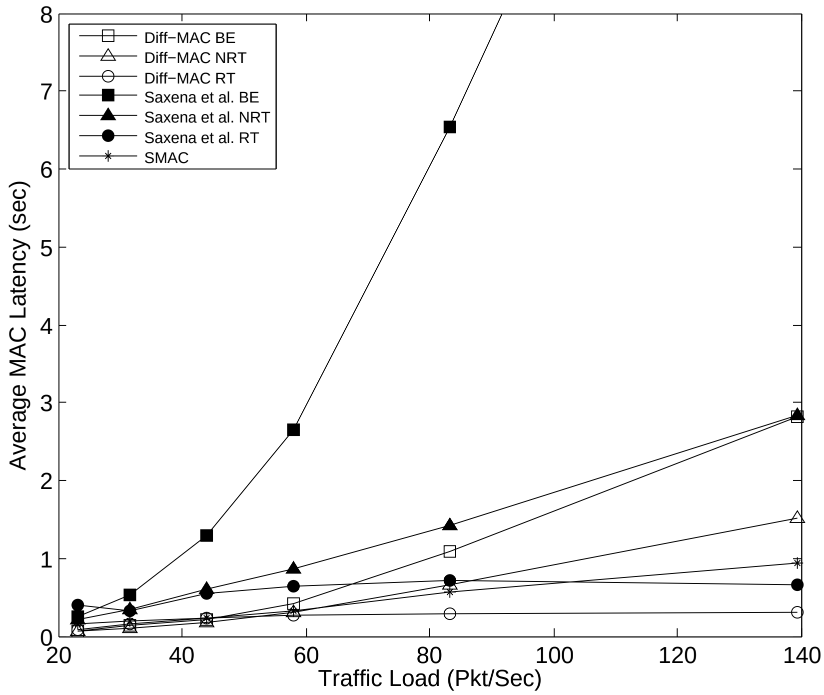


Figure 4.12. Comparative medium access latency

consumption of Saxena et al. MAC places between the Diff-MAC and SMAC. When achieved throughput and latency performances of Diff-MAC considered in conjunction with Fig. 4.14, the energy expenditure in the heavy traffic conditions shown in Fig. 4.13 seems to be tolerable.

Depending on the application requirements, deployment area of the WMSNs can be relatively large areas. Since packets are carried in a hop-by-hop manner in sensor networks, packets created by the sensor nodes further from the sink have to traverse more hops and delivery of these packets takes more time than the ones created near to sink. However, critical events may also occur at the far end of the observation field and has to be relayed within a reasonable time duration. To observe the contributions of WFQ and TNHBP, average source-to-sink latencies and average successful packet delivery ratios of the NRT and BE traffic depicted in Figures 4.15 - 4.18[1] depending on the distances of the sensor nodes to sink.

[1]Figures 4.15 - 4.18 are obtained under the heavily loaded (Load Type 6) traffic conditions to see the contributions of WFQ and TNHBP clearly.

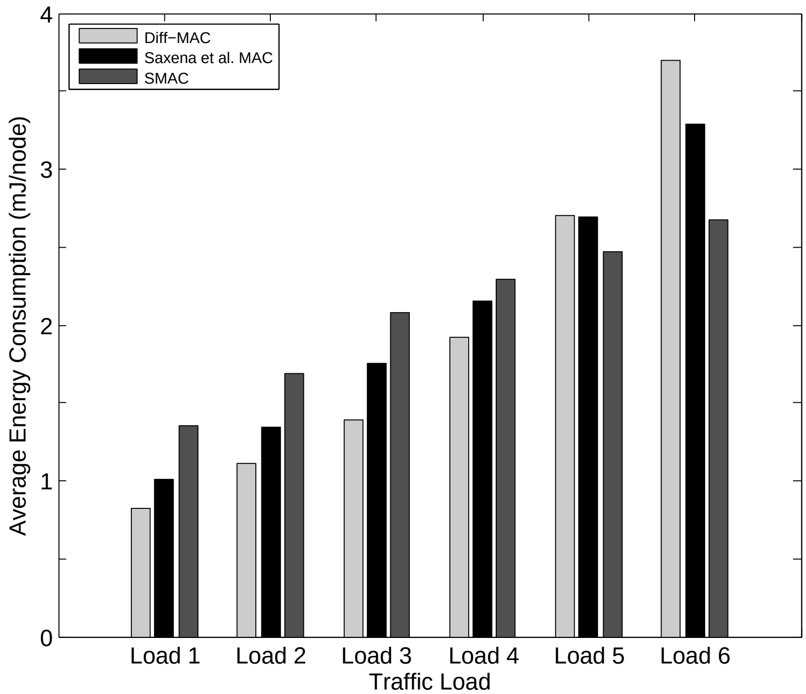


Figure 4.13. Comparative energy consumption

Traversing more hops brings an extra delay for packets coming from further sensor nodes. Moreover, explicit prioritization of the packet scheduler introduces a longer queueing delay for the lower priority traffic. Fig. 4.15 and Fig. 4.16 present the average source-to-sink latencies of NRT and BE traffic respectively. The latency of the each received packet by the sink is classified based on both packet's traffic type and traversed hop count. The maximum hop count in our simulations is measured as 10 and average distance to sink distribution of the sensor nodes in our test cases can be found in Table 4.3. When we look at the latencies of the packets based on their hop count, the difference between Diff-MAC and Saxena et al. MAC is not quite much for the packets created near the sink node. However, performance of the Saxena et al. MAC worsens as the hop-count increases. Meanwhile, Diff-MAC provides fairness among all sensor nodes by minimizing the maximum of the packet latencies and tries to distribute delay evenly by integrating the intra-node and intra-queue prioritization mechanisms. As we mentioned in Section 3.4, TNHBP increases the priority of the packet as it traverses more hops and relays faster as it gets closer to the sink. Additionally, WFQ gives low priority packets a chance to reserve the medium rather than serving the higher priority

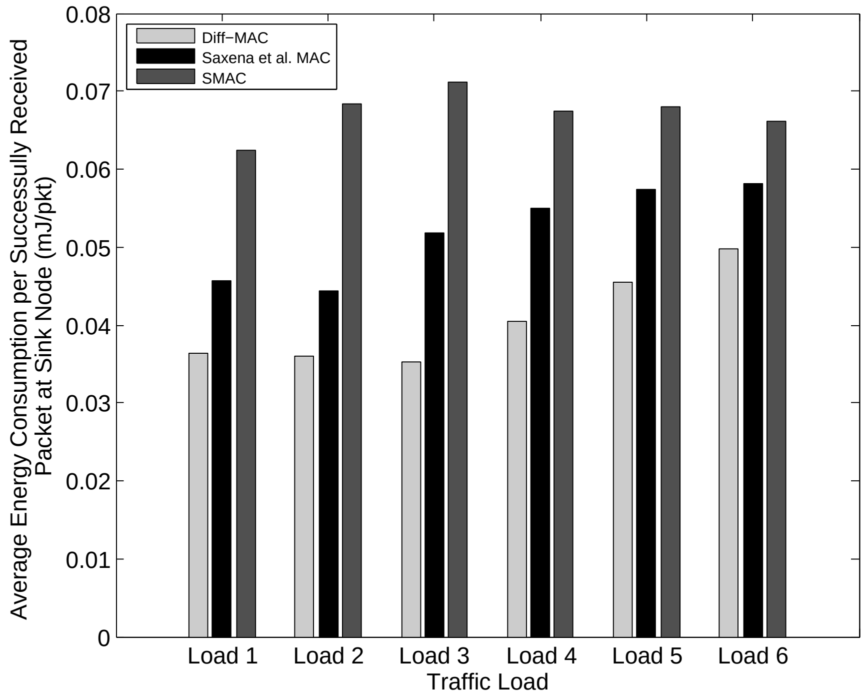


Figure 4.14. Comparative energy consumption per successfully received packet at the sink node

packets always first. That's why, Diff-MAC keeps the latency deviations of the packets traversing different hops until the sink and prevents intolerable performances. On the other hand, Saxena et al. MAC introduces beyond the limit latencies for lower priority and distant created traffic.

In sensor networks, packets generated by the sensor nodes that are further from the sink are not only delivered with high latencies but also more vulnerable to collisions and buffer overflows. Hence, the probability of successful packet delivery drops as the distance between the source and destination increases. Diff-MAC overcomes this problem and provides fair delivery of the packets among all sensor nodes regardless of their geographical position in the network by integrating WFQ and TNHBP. Fig. 4.17 and Fig. 4.18 present the average successful packet delivery ratio of the NRT and BE traffic. Both Diff-MAC and Saxena et al. MAC achieves higher delivery ratios for closer sensor nodes. As the distance to sink node increases, successful packet delivery ratio of the Saxena et al. MAC drops sharply. On the other hand, Diff-MAC preserves

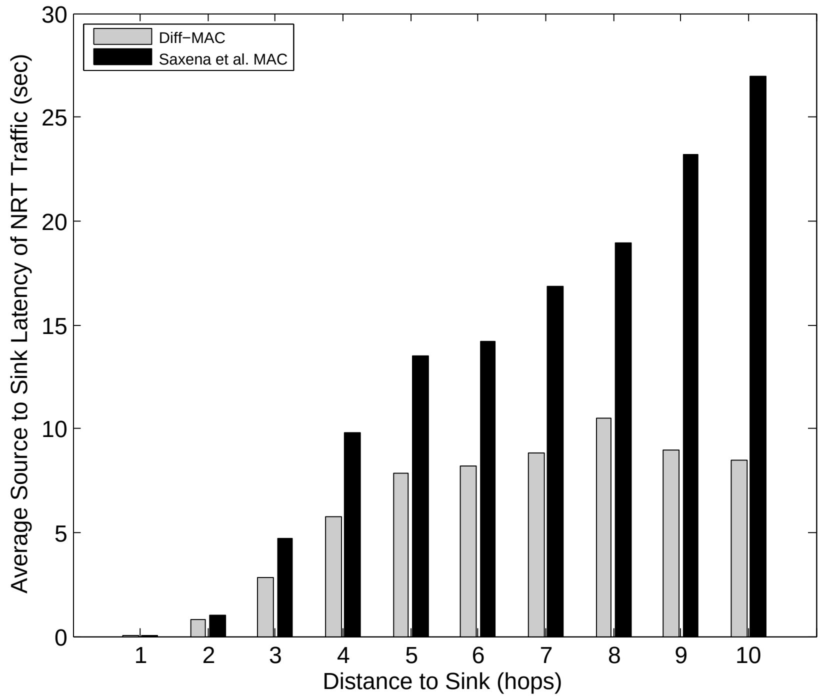


Figure 4.15. Effect of WFQ and TNHBP on the source to sink delay of NRT traffic

the successful packet delivery ratio as the distance increases by adopting WFQ and TNHBP.

When we look at Fig. 4.17 and Fig. 4.18 closer, Saxena et al. MAC performs slightly better than Diff-MAC for closer sensor nodes. Since TNHBP prioritize the packets based on their number of traversed hops, the sensor nodes closer to sink always receive higher priority packets originated from the distant sensor nodes. Therefore, newly created packets in the closer sensor nodes have to wait for the other higher priority packets which have been received from the further sensor nodes. This gives Saxena et al. MAC the opportunity to successfully deliver more packets than Diff-MAC which is generated by the sensor nodes closer to the sink.

However, we assumed perfect-reception-within-range model as mentioned earlier. This assumption prevents us to make a reliable and accurate performance evaluation especially in hop-based cases. Therefore, we adopted a realistic link layer model described in Section 4.2 which takes both the wireless channel and the radio into account.

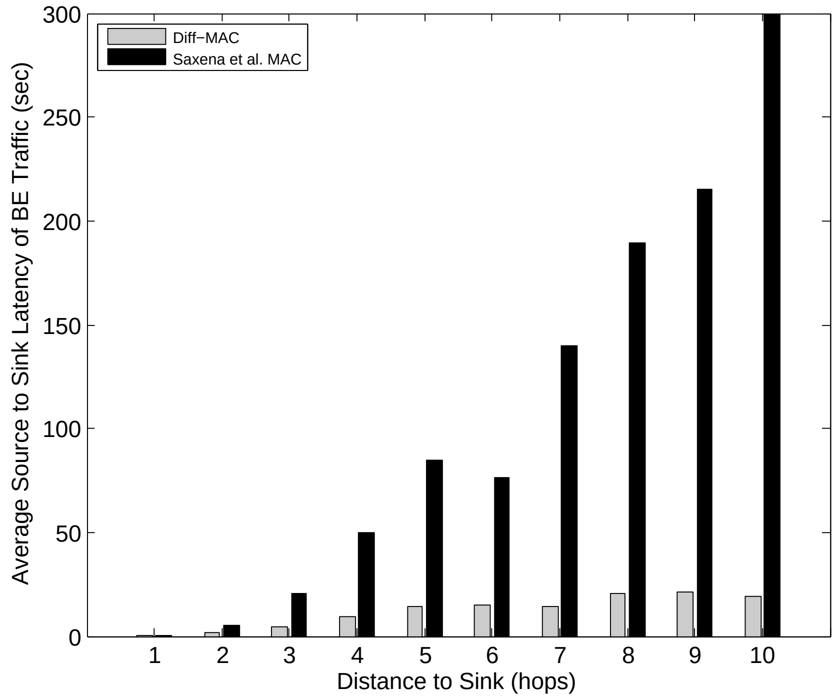


Figure 4.16. Effect of WFQ and TNHBP on the source to sink delay of BE traffic

Thus, we have had the opportunity to obtain more realistic results and observe the effect of the link layer.

Fig. 4.19 and Fig. 4.20 obtained by considering both the wireless medium and the radio by integrating the realistic link layer model described in Section 4.2. Integration of the link layer model decreases the successful packet delivery ratio of the NRT and BE traffic unsurprisingly. However, Diff-MAC still manages to be fair among the sensor nodes by utilizing WFQ and TNHBP relative to Saxena et al. MAC which performs very poor for distant sensor nodes. Moreover, Fig. 4.19 and Fig. 4.20 reveals the necessity for a reliable routing protocol which takes the link layer issues into consideration since GPSR tries to relay the packets to the closest one to the sink among its neighboring sensor nodes. Hence, GPSR chooses the farther neighbor node without considering the channel conditions and radio capabilities to deliver the packet to its destination as fast as possible.

Table 4.3. Distribution of Average Distance to Sink

Distance to Sink (hops)	**# Sensor Nodes**	**Percentage (%)**
1	11	2.75
2	27	6.75
3	45	11.25
4	54	13.5
5	63	15.75
6	76	19
7	67	16.75
8	36	9
9	15	3.75
10	6	1.5

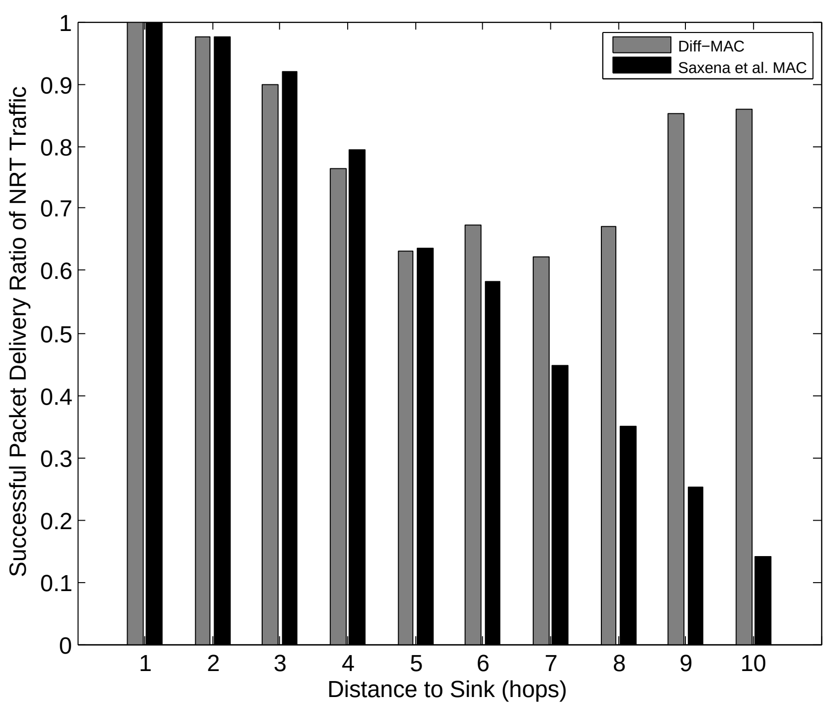


Figure 4.17. Effect of WFQ and TNHBP on the fair delivery of NRT traffic

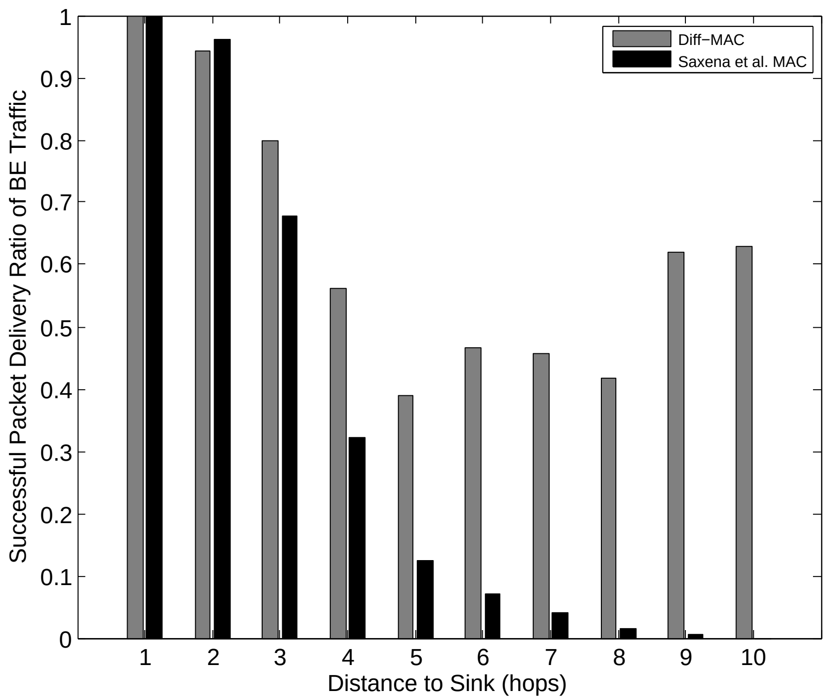


Figure 4.18. Effect of WFQ and TNHBP on the fair delivery of BE traffic

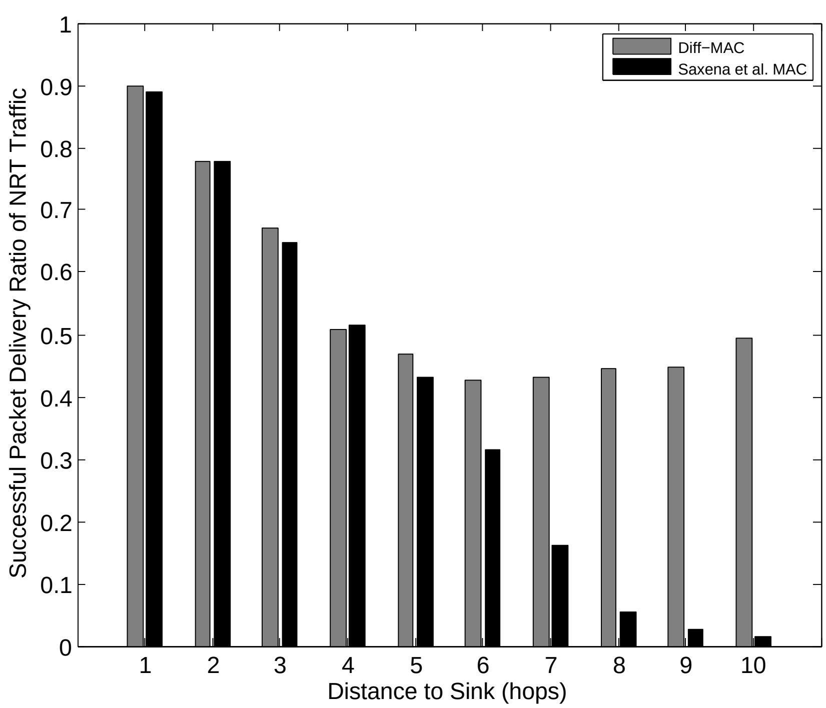


Figure 4.19. Effect of WFQ and TNHBP on the fair delivery of NRT traffic with realistic link layer model

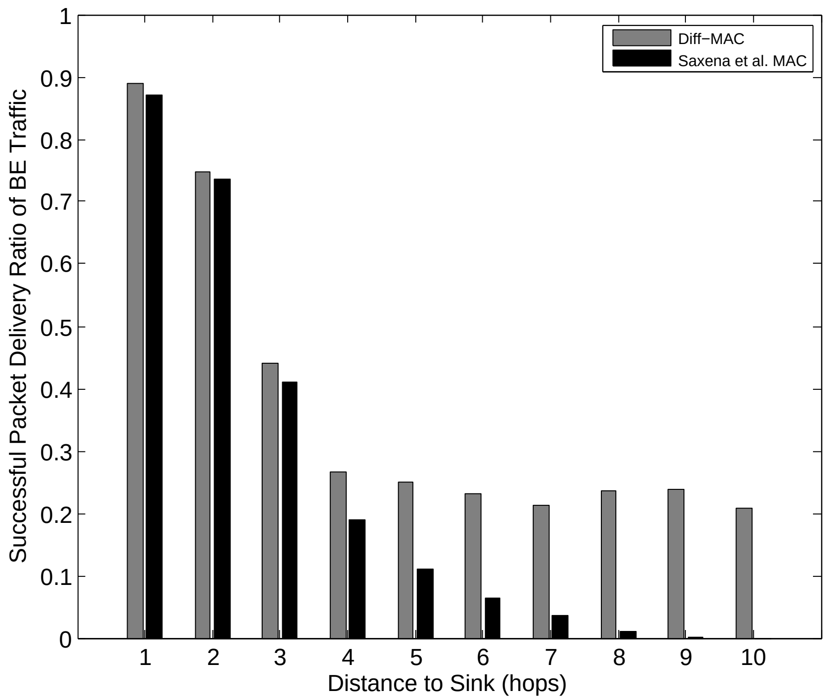


Figure 4.20. Effect of WFQ and TNHBP on the fair delivery of BE traffic with realistic link layer model

5. CONCLUSIONS

In this thesis, after an extensive survey of QoS provisioning in WMSNs and identifying the required properties of a QoS-aware MAC protocol, we proposed Diff-MAC; a novel QoS-aware and hybrid-priority MAC protocol for heterogeneous WMSNs. Firstly, we explored QoS perspectives for WMSNs and classified the sensory applications based on their data delivery models in order to define the required QoS parameters for accurate performance evaluation of QoS mechanisms in WMSNs. WMSN-specific challenges for QoS-provisioning are listed and service differentiation methods in the literature examined. Properties of a well-designed QoS-aware MAC protocol for WMSNs are pointed out and existing protocols surveyed with their advantages and disadvantages. QoS-aware MAC layer design tradeoffs comparatively evaluated.

After exploring the QoS Provisioning issues in sensor networks, design and architecture details of Diff-MAC explained in detail. Diff-MAC uses a multi-queue architecture and coordinates the medium access of each traffic class by using effective service differentiation mechanisms. Fragmentation and message passing features of Diff-MAC reduces the retransmission cost in case of MAC failures while CW size adaptation mechanism tries to balance both energy consumption and delay. Moreover, dynamic DC mechanism prevents either unnecessary idle waiting and early sleeping.

Traversed Number of Hops Based Prioritization (TNHBP) and Weighted Fair Queueing (WFQ) defined for providing fair delivery of the data among all sensor nodes and among all traffic classes respectively to avoid intolerable performances. Integration of intra-queue prioritization mechanism prevents waste of network resources by giving precedence to more invested packets in terms of energy, bandwidth, memory and time. Proposed intra-node prioritization mechanism gives chance to all traffic classes for accessing the medium and tries to bound the worst case performances of lower priority packets.

A real-life surveillance application scenario introduced as a motivation for our protocol and this broad scenario used in all simulation runs for performance evaluation of Diff-MAC. Results of extensive simulation runs showed that Diff-MAC outperforms both Saxena et al. MAC and SMAC in terms of throughput by achieving higher performance. Also Diff-MAC reduces the source-to-sink latencies of all traffic classes with effective service differentiation mechanisms. SMAC does not make any differentiation between traffic classes while Saxena et al. MAC introduces intolerable performances for BE traffic. For pure performance evaluation of the MAC layer, MAC latencies also investigated and obtained results are similar to source-to-sink latencies. Diff-MAC consumes less energy in lightly loaded traffic conditions while consumes more in heavily loaded traffic conditions since it adapts to current network conditions well. Energy expenditure variations of SMAC is relatively low due to pre-determined static duty cycling. However, more energy expenditure of Diff-MAC in heavily loaded traffic conditions might be tolerable when higher throughput and lower latency performance considered.

For effective performance evaluation of TNHBP and WFQ, successful packet delivery ratios and source-to-sink latencies of the produced packets by the sensor nodes are examined based on their distance to sink node and compared with Saxena et al. MAC. Diff-MAC provides fair delivery of the packets regardless of their distance between the owner sensor node of the packet and sink. Moreover, it minimizes the maximum of the packet latencies originated from different locations of the sensor network. On the other hand, packet latencies of the Saxena et al. MAC increases as the distance increases and finally causes intolerable performance for the packets created by the furthest sensor nodes. Similarly, successful packet delivery ratio of the sensor nodes decreases as the distance to sink increases since these packets are more vulnerable to collisions and buffer overflow. However, Diff-MAC gives precedence to more traversed packets and tries to fairly deliver all the packet regardless of their originating location.

As the future work, a mechanism for sleep-listen synchronization between neighboring sensor nodes can be implemented to reduce the packet latencies at the cost of control overhead. Also, performance of the QoS support might be increased by utilizing more decision parameters for packet prioritization like remaining hop count, remaining energy or buffer load. Moreover, integration of more decision parameters may lead to a more effective cross-layer solution by melting down both MAC and network layer protocols into a single layer rather than the traditional layered QoS approaches.

APPENDIX A: OPNET IMPLEMENTATION OF DIFF-MAC

Since implementation of Diff-MAC on OPNET Modeler covered most of the thesis preparation process, encountered problems during the code generation will be discussed in this Appendix. Although there is an accumulated know-how in the Wireless Sensor Networks Research Group (WiSe), implementation of Diff-MAC was not very easy which took nearly eight months including the removal of the bugs. Remote access of OPNET license server located in the ETA building was achieved by Cisco VPN Manager and OPNET version 14.A.PL2 was used.

One of the major problems that we suffer during the code development process was lack of adequate debugging facilities. Since the source code cannot be executed step-by-step, it is very hard to find out the faulty parts. Moreover, each entity in the network topology runs the same code simultaneously. Hence, the parallel execution of the code brings an additional challenge for debugging. We used a primitive but highly efficient method to overcome the debugging problem. Simple output messages generated at the beginning and end of each routine and written to a file. Each message includes sensor node identifier, simulation time, current state of the node, etc. By this way, a kind of detailed log file created during the execution. In the case of a crash or malfunctioning, this log file can be referred to find out the source. However, this log file can be used just for short simulation runs since it becomes very hard to track the faults as the size of the file grows[2] .

Since OPNET has its own procedures and packages, it is not enough to be a software developer in order to design and implement protocols on OPNET. Developer must be familiar with the OPNET specific kernel procedures and must know what they are used for. Hence, considerable part of the implementation process spent by reading the help document of OPNET.

[2]A simple log file generated for a 20-second simulation run of a 100-node network contains approximately 30-40 MB of ASCII information

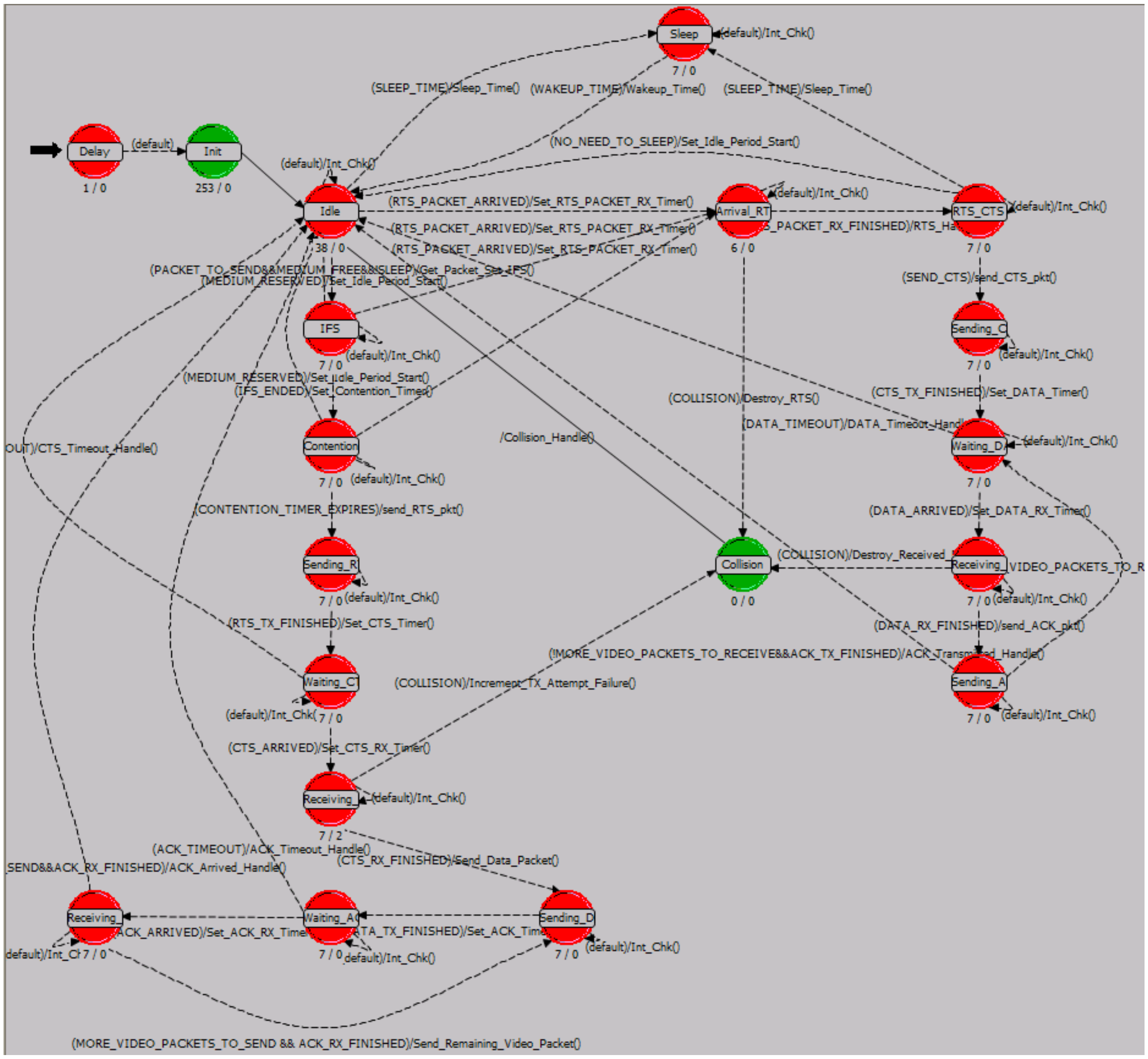


Figure A.1. Complete state transition diagram of Diff-MAC

It is not enough to implement just the MAC layer for obtaining results from OPNET. You must develop a complete system including the routing layer, traffic generation, node deployment, etc. and each of these issues solved by the WiSe Group. Hence, we did not only implement Diff-MAC but also remaining parts of a complete sensor network. Fig. A.1 depicts the complete state transition diagram of Diff-MAC which a simplified version of it was given in Fig. 3.1. Fig A.2 depicts the OPNET process model of Diff-MAC. BE and NRT traffic generators can be seen easily. Target_Detector module used for video detection of the target as depicted in Fig. 4.7. QoS_MAC_Data_Handler module is the heart of Diff-MAC and handles majority of the networking issues. Rx and Tx modules receive data from and send data to the Antenna module.

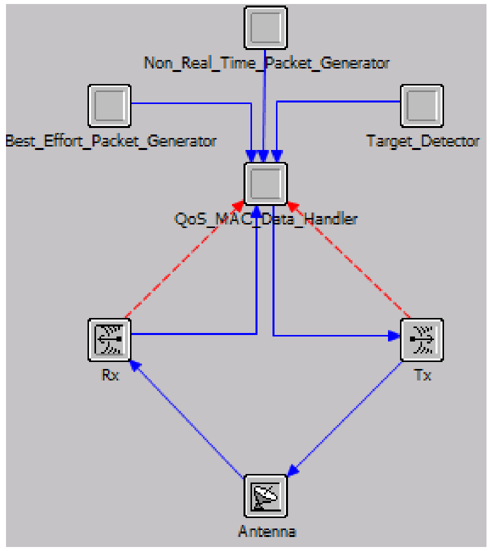


Figure A.2. Process model of Diff-MAC

Another problem was the high computational power requirement of the discrete event simulations. Ordinary desktop PCs are far from meeting the requirements and causes endless execution times. That's why, An 8-core cluster machine used for simulation runs and the total time spent depicted in Table A.1.

Table A.1. Total Time Spent for Simulation Runs

	# of Test Cases	**# of Repetitions**	**Total Time (hours)**
Diff-MAC	6	10	120
Diff-MAC with RLLM [3]	1	10	50
Saxena et al. MAC	6	10	110
Saxena et al. MAC with RLLM	1	10	35
SMAC 10% DC	6	10	20
SMAC 50% DC	6	10	30
SMAC 90% DC	6	10	45
Grand Total			**410**

During the design phase of Diff-MAC, we decided to develop the code in a modular manner. From detection mechanism to adaptation, to queue management can be changed by easily selecting the related parameters in the config node. Moreover,

[3] RLLM stands for Realistic Link Layer Model and described in Section 4.2.

enlightening comment lines inserted every part of the source code to help the other developers who will integrate new add-ons for Diff-MAC. As a matter of the fact, other WiSe researchers have already started to develop a QoS-aware routing protocol on top of the Diff-MAC.

REFERENCES

1. I.F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, *A survey on sensor networks*, IEEE Communications Magazine vol. 40, no. 8, pp. 104112, 2002.

2. I. Akyildiz, T. Melodia, K. Chowdhury, *A survey on wireless multimedia sensor networks*, Computer Networks vol. 51, no. 4, pp. 921-960, 2007.

3. International Telecommunication Union (ITU) Recommendation E.800 (09/08), *Terms and definitions related to the quality of telecommunication services*, 2008.

4. K. Nguyen, T. Nguyen, C. Chaing, and M. Motani, *A Prioritized MAC Protocol for Multihop, Event-driven Wireless Sensor Networks*, IEEE Conference on Communications and Electronics, October 2006.

5. L. Yang, I. Elhanany and Q. Hairong, *An Energy-Efficient QoS-Aware Media Access Protocol for Wireless Sensor Networks*, Proceedings of the International Conference on Mobile Adhoc and Sensor Networks 2005, November 2005.

6. Kwang-Jin Paek, Jongwan Kim, Ui-Sung Song, Chong-Sun Hwang, *Priority-Based Medium Access Control Protocol for Providing QoS in Wireless Sensor Networks*, LETTER, IEICE Trans. Inf. & Syst., Vol.E90-D, No.9, September 2007.

7. Navrati Saxena, Abhishek Roy, Jitae Shin, *Dynamic duty cycle and adaptive contention window based QoS-MAC protocol for wireless multimedia sensor networks*, Computer Networks vol. 52 no. 13, pp. 2532-2542, 2008.

8. Z. Liu, I. Elhanany, *RL-MAC: A QoS-Aware Reinforcement Learning based MAC Protocol for Wireless Sensor Networks*, IEEE Conference on Networking, Sensing and Control, Ft. Lauderdale, FL, April, 2006.

9. Ines Slama, Bharat Shrestha, Badii Jouaber, Djamal Zeghlachey, *RA hybrid MAC*

with prioritization for wireless sensor networks, The 33rd IEEE Conference on Local Computer Networks (LCN), Montreal, Quebec, Canada, October 2008.

10. N. Saxena, R. Abhishek and J. Shin, *A QoS-Based Energy-Aware MAC Protocol for Wireless Multimedia Sensor Networks*, IEEE Vehicular Technology Conference (VTC), Marina Bay, Singapore, 2008.

11. W. Ye, J. Heidemann and D. Estrin, *Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks*, IEEE/ACM Transactions on Networking, vol. 12, no. 3, June 2004.

12. C. C. Enz, A. El-Hoiydi, J-D. Decotignie, V. Peiris, *WiseNET: An Ultralow-Power Wireless Sensor Network Solution*, IEEE Computer, Volume: 37, Issue: 8, August 2004.

13. V. Rajendran, K. Obraczka, J.J. Garcia-Luna-Aceves, *Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks*, he First ACM Conference on Embedded Networked Sensor Systems (Sensys03), Los Angeles, CA, USA, November 2003.

14. K. Jamieson, H. Balakrishnan, and Y. C. Tay, *Sift: A MAC protocol for event-driven wireless sensor networks*, Technical report, MIT, May 2003.

15. G. Lu, B. Krishnamachari, C.S. Raghavendra, *An Adaptive Energy-efficient and Low-latency MAC for Data Gathering in Wireless Sensor Networks*, 18th International Parallel and Distributed Processing Symposium, April 2004.

16. T.V. Dam and K. Langendoen, *An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks*, The First ACM Conference on Embedded Networked Sensor Systems (Sensys03), Los Angeles, CA, USA, November 2003.

17. P. Lin, C. Qiao, and X. Wang, *Medium Access Control with a Dynamic Duty Cycle for Sensor Networks*, IEEE Wireless Communications and Networking Conference,

March 2004.

18. I. Demirkol, F. Alagöz, H. Delic, and C. Ersoy, *Wireless Sensor Networks for Intrusion Detection: Packet Traffic Modeling*, IEEE Communications Letters, vol. 10, no. 1, pp.22-24, 2006.

19. I. Demirkol and C. Ersoy, *Energy and delay optimized contention for wireless sensor networks*, Computer Networks, Vol.53, pp.2106-2119, August 2009.

20. Broch, J., Maltz, D., Johnson, D., Hu, Y., and Jetcheva, J., *A performance comparison of multi-hop wireless ad hoc network routing protocols*, 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom '98) , Dallas, Texas, USA, August 1998.

21. "Opnet Modeler," 2009. [Online]. Available: http://www.opnet.com/products/modeler/home.htm

22. B. Karp and H. T. Kung, *GPSR: greedy perimeter stateless routing for wireless networks*, MOBICOM, 2000.

23. H. Xiao, W.K.G. Seah, A. Lo, and K. C. Chua, *A Flexible Quality of Service Model for Mobile Ad-Hoc Networks*, IEEE VTC2000-spring, Tokyo, Japan, May 2000.

24. S-B. Lee and A.T. Campbell, *INSIGNIA: In-band Signalling Support for QOS in Mobile Ad Hoc Networks*, Proc of 5th International Workshop on Mobile Multimedia Communications (MoMuC,98), Berlin, Germany, October 1998.

25. J.L. Sobrinho and A.S. Krishnakumar, *Quality-of-Service in Ad Hoc Carrier Sense Multiple Access Wireless Networks*, IEEE Journal on Selected Areas in Communications, vol. 17, no. 8, August 1999.

26. C. Lu, B. M. Blum, T. Abdelzaher, J. Stankovic, T. He, *RAP: A Real-Time Communication Architecture for Large-Scale Wireless Sensor Networks*, 8th IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), 2002.

27. Thomas Watteyne and Isabelle Aug-Blum, *Proposition of a Hard Real-Time MAC Protocol for Wireless Sensor Networks*, IEEE Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS), Atlanta, USA, September 2005.

28. M. Caccamo, L. Y. Zhang, L. Sha and G. Buttazzo, *An Implicit Prioritized Access Protocol for Wireless Sensor Networks*, Proceedings of the IEEE Real-Time Systems Symposium (RTSS), Austin, Texas, December 2002.

29. I. Rhee, A. Warrier, and L. Xu, *Randomized Dining Philosophers toTDMA Scheduling in Wireless Sensor Networks*, Computer Science Department, North Carolina State University, Raleigh, NC, 2004.

30. I. Rhee, A. Warrier, M. Aia, and J. Min, *Z-MAC: A hybrid MAC for wireless sensor networks*, Proc. of the 3rd ACM Conference on Embedded Networked Sensor Systems (SenSys), San Diego, CA, November 2005.

31. D. Bertsekas and R. Gallager, *Data Networks*, Prentice Hall, 1987.

32. A. Parekh and R. Gallager,*A generalized processor sharing approach to flow control in integrated services networks: The single-node case*, Proc. IEEE INFORCOM, 1992.

33. G. S. Ahn, A. T. Campbell, A. Veres and L.H. Sun, *SWAN: Service Differentiation in Stateless Wireless Ad Hoc Networks*, IEEE INFOCOM'2002, June 2002.

34. C. Lu, B. M. Blum, T. F. Abdelzaher, J. A. Stankovic, and T. He, *RAP: A Real-Time Communication Architecture for Large-Scale Wireless Sensor Networks*, IEEE RTAS 2002, September 2002.

35. T. He, J. Stankovic, C. Lu, and T. Abdelzaher, *SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks*, IEEE International Conference on Distributed Computing Systems (ICDCS), 2003.

36. E. Felemban, C. Lee and E. Ekici, *MMSPEED: Multipath Multi-SPEED Protocol for QoS Guarantee of Reliability and Timeliness in Wirelss Sensor Networks*, IEEE Transactions on Mobile Computing vol.5, no.6, pp. 738-754, 2006.

37. K. Akkaya and M. Younis, *An energy-aware QoS routing protocol for wireless sensor networks*, 23rd International Conference on Distributed Computing Systems Workshops (ICDCS 2003 Workshops), Providence, RI, USA, May 2003.

38. Xiaoxia Huang and Yuguang Fang, *Multiconstrained QoS Multipath Routing in Wireless Sensor Networks*, ACM Wireless Networks, vol.14, no.4, pp. 465-478, 2008.

39. A. Zaballos, A. Vallejo, P. Terradellas and J. M. Selga, *A genetic-based QoS aware routing for ubiquitous sensor networks*, 5th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Marrakech, Morocco, October 2009.

40. M. Yu, A. Malvankar, W. Su, and S. Y. Foo, *A Link Availability-Based QoS-Aware Routing Protocol for Mobile Ad hoc Sensor Networks*, Computer Communications, (Elsevier), vol.30, no.18, pp. 3823-3831, December 2007.

41. Y.G. Iyer, S. Gandham, S. Venkatesan, *STCP: a generic transport layer protocol for wireless sensor networks*, IEEE ICCCN 2005, San Diego, CA, October 2005.

42. B. Hull, K. Jamieson, H. Balakrishnan, *Mitigating congestion in wireless sensor networks*, ACM Sensys04, Baltimore, MD, November 2004.

43. C. Wang, B. Li, K. Sohraby, M. Daneshmand, Y. Hu, *Upstream congestion control in wireless sensor networks through cross-layer optimization*, IEEE Journal on Selected Areas in Communications vol.25, no.4, pp.786795, 2007.

44. C.T. Ee, R. Bajcsy, *Congestion control and fairness for many-to one routing in sensor networks*, ACM Sensys04, Baltimore, MD, November 2004.

45. Mohammad Hossien Yaghmaee, Donald A. Adjeroh, *Priority-based rate control for service differentiation and congestion control in wireless multimedia sensor networks*, Computer Networks vol.53, no.11, pp. 1798-1811, 2009.

46. Y.G. Iyer, S. Gandham, S. Venkatesan, *STCP: a generic transport layer protocol for wireless sensor networks*, 14th IEEE International Conference on Computer Communications and Networks, San Diego, CA, 2005.

47. Y. Zhou, M.R. Lyu, *PORT: a price-oriented reliable transport protocol for wireless sensor network*, 16th IEEE International Symposium on Software Reliability Engineering (ISSRE), Chicago, IL, 2005.

48. Y. Sankarasubramaniam, O.B. Akan, I.F. Akyilidiz, *ESRT: event-to-sink reliable transport in wireless sensor networks*, MobiHoc, Annapolis, MD, 2003.

49. C.-Y. Wan, S.B. Eisenman, A.T. Campbell, *CODA: Congestion detection and avoidance in sensor networks*, The First ACM Conference on Embedded Networked Sensor Systems (Sensys03), Los Angeles, CA, USA, November 2003.

50. Z. Xiong, A. Liveris, and S. Cheng, *Distributed source coding for sensor networks*, IEEE Signal Processing Magazine, vol.21, no.5, pp.8094, 2004.

51. J. Yick, B. Mukherjee, and D Ghosal, *Wireless sensor network survey*, Computer Networks, vol.52, no.12, pp. 2292-2330, August 2008.

52. S. Tilak, N. Abu-Ghazaleh and W. Heinzelman, *A taxonomy of wireless microsensor network communication models*, ACM Mobile Computing and Communication Review (MC2R), June 2002.

53. P. Kulkarni, D. Ganesan, P. J. Shenoy, and Q. Lu, *SensEye: a multi-tier camera sensor network*, 13th ACM International Conference on Multimedia, Singapore, November 2005.

54. M. Perillo and W. Heinzelman, *Providing Application QoS Through Intelligent Sen-*

sor Management, 1st IEEE International Workshop on Sensor Network Protocols and Applications (SNPA '03), May 2003.

55. Ines Slama, Badii Jouaber, Djamal Zeghlache, *Optimal Power management scheme for Heterogeneous Wireless Sensor Networks: Lifetime Maximization under QoS and Energy Constraints*, International Conference on Networking and Services (ICNS'07), 2007.

56. Y. Xiao, H. Chen, K. Wu, C. Liu, B. Sun, *Maximizing Network Lifetime under QoS constraints in Wireless Sensor Networks*, 49th IEEE Global Telecommunications Conference (GLOBECOM'06), San Francisco, CA, December 2006.

57. P. Corke, P. Valencia, P. Sikka, T.Wark, L. Overs, *Long-Duration Solar-Powered Wireless Sensor Networks*, 4th workshop on Embedded Networked Sensors, Cork, Ireland, June 2007.

58. J. Taneja, J. Jeong, D. Culler, *Design, Modeling, and Capacity Planning for Micro-solar Power Sensor Networks*, International Conference on Information Processing in Sensor Networks (IPSN '08), 2008.

59. B. Krishnamachari, D. Estrin, and S. Wicker, *The Impact of data aggregation in wireless sensor networks*, International Workshop on Distributed Event-Based Sytems, Vienna, Austria, July 2002.

60. C. Intanagonwiwat, R. Govindan, D. Estrin,J. Heidemann, F. Silva, *Directed Diffusion for Wireless Sensor Networking*, IEEE/ACM Transactions on Networking, vol.11, no.1, pp. 2- 16, 2003.

61. Crossbow Technology, http://www.xbow.com, 2009.

62. Chipcon, CC1000 low power radio transceiver, http://www.chipcon.com, 2007.

63. Dan Tao, Huadong Ma, and Liang Liu, *Coverage-Enhancing Algorithm for Directional Sensor Networks*, Lecture Notes in Computer Science, Springer Berlin /

Heidelberg, pp. 256-267, 2006.

64. W. Cheng, S. Li, X. Liao, S. Changxiang, H. Chen, *Maximal Coverage Scheduling in Randomly Deployed Directional Sensor Network*, Proceedings of the 2007 International Conference on Parallel Processing Workshops (ICPPW), XiAn, China, 2007.

65. D. Chen and P. K. Varshney, *QoS support in wireless sensor networks: A survey*, International Conference on Wireless Networks (ICWN '04), pp. 227-233, Las Vegas, USA, June 2004.

66. A. Demers, S. Keshav, S. Shenkar, *Analysis and simulation of a fair queueing algorithm*, Internetworking Research and Experience, 1990.

67. M. Zuniga, and B Krishnamachari, *Analyzing the Transitional Region in Low Power Wireless Links*, IEEE Sensor and Ad Hoc Communications and Networks (SECON), vol.1, pp. 517-526, Santa Clara, Canada, October 2004.

68. Theodore S. Rappapport, *Wireless Communications: Principles and Practice*, Prentice Hall.

69. K. Sohrabi, B. Manriquez, and G. Pottie, *Near Ground Wideband Channel Measurement*, IEEE Vehicular Technology Conference, vol.1, pp. 571-574, 1999.

70. R. Braden, D. Clark, S. Shenker, *Integrated Services in the Internet Architecture - An overview*, IETF RFC 1663, June 1994.

71. S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss, *An Architecture for Differentiated Services*, RFC 2475, IETF, December 1998.