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A New Cross-Layer QoS-Provisioning Architecture in Wireless Multimedia Sensor Networks

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Abstract

Emerging applications in automation, medical imaging, traffic monitoring and surveillance need real-time data transmission over Wireless Sensor Networks (WSNs). Guaranteeing Quality of Service (QoS) for real-time traffic over WSNs creates new challenges. Rapid penetration of smart devices, standardization of Machine Type Communications (MTC) in next generation 5G wireless networks have added new dimensions in these challenges. In order to satisfy such precise QoS constraints, in this paper, we propose a new cross-layer QoS-provisioning strategy in Wireless Multimedia Sensor Networks (WMSNs). The network layer performs statistical estimation of sensory QoS parameters. Identifying QoS-routing problem with multiple objectives as NP-complete, it discovers near-optimal QoS-routes by using evolutionary genetic algorithms. Subsequently, the Medium Access Control (MAC) layer classifies the packets, automatically adapts the contention window, based on QoS requirements and transmits the data by using routing information obtained by the network layer. Performance analysis is carried out to get an estimate of the overall system. Through the simulation results, it is manifested that the proposed strategy is able to achieve better throughput and significant lower delay, at the expense of negligible energy consumption, in comparison to existing WMSN QoS protocols.

Keywords: Wireless multimedia sensor networks, QoS-provisioning, Cross-layer architecture, Genetic algorithms

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1. Introduction

Wireless sensor networks (WSNs) [1] are made up of small sensor nodes, equipped with sensing, processing and communication capabilities. As sensor nodes typically monitor physical or environmental conditions, such as temperature, sound, humidity and pressure, the sensory data is comparatively small in size and discrimination free. Therefore, relatively less research works exist on Quality of Service (QoS) in WSNs. However, the introduction of smart, wearable sensory devices and penetration of new applications, like automation, medical imaging, and traffic monitoring are setting the stage for Wireless Multimedia Sensor Networks (WMSNs) [2]. These sets of new applications require some specific QoS guarantee in sensor networks. However, conflicting requirements of multiple QoS parameters raise significant new challenges in WMSNs. Therefore, achieving a necessary and optimal balance among the conflicting QoS parameters is essential in QoS-provisioning in WMSNs.

The survey in [2] discusses the existing works on WMSNs with comparative performance analysis. An in-depth look into the existing sensory QoS protocols [2] reveals that most of the solutions suffer from three major constraints: (a) a single QoS parameter, like end-to-end delay or throughput is considered; (b) multiple QoS parameters are combined to form a single scalar objective function; (c) effects of QoS guarantee across both the network and Medium Access Control (MAC) layer are not explored.

In order to improve QoS in wireless networks, some cross-layer approaches are studied [3]. These cross-layer designs exchange and share the information between the upper layer and the lower layer. At the initial stage, many cross-layer designs aim at maximizing spectral efficiency by using a Forward Error Correction (FEC) mechanism [4], hybrid automatic repeat request [5] and Adaptive Modulation and Coding (AMC) [6]. Contrastively, a priority-based MAC scheduler for multiple connections is proposed in [7], where each connection has a priority according to QoS constraints. In order to maximize spectral efficiency, AMC scheme for each connection is assigned at physical (PHY) layer. Through this cross-layer approach, diverse QoS guarantee and high bandwidth utilization can be achieved. For the cognitive radio wireless networks, spectrum sensing policy at PHY layer is integrated with the packet scheduling at MAC layer [8]. This cross-layer based opportunistic MAC protocol over the cognitive radio wireless networks focuses on how the secondary users sense and utilize the available radio frequency spectrum without the interference to the primary users. In [9], a cross-layer scheme based on application layer and MAC layer for H.264 video traffic is proposed. This scheme consists of a data partitioning according to importance of data at application layer and appropriate QoS marking algorithm at MAC layer.

In this point of view, we also believe that an end-to-end application-specific QoS-provisioning can only be achieved by providing suitable QoS guarantee across different layers, primarily network layer and MAC layer. This motivates us to look for a new cross-layer QoS-provisioning architecture for WMSNs. More specifically our contributions are enumerated below:

(1) We illustrate a new cross-layer QoS-provisioning architecture for WMSNs. This framework spans across both network and MAC layers. While the network layer attempts to achieve optimal routes with specific QoS requirements, the MAC layer is in charge of packet classification and delivery.

(2) For network layer QoS guarantee, we first make statistical estimation of QoS parameters across WMSNs. Identifying the problem as NP-complete, we provide a near-optimal QoS

routing solution based on Multi-Objective Genetic Algorithms (MOGA).

(3) Subsequently, QoS-provisioning in WMSN MAC is performed based on CSMA-CA approach. It adaptively adjusts the contention window according to both the traffic types and wireless channel characteristics. The overall performance is analyzed by developing a suitable performance modeling.

(4) Simulation results delineate that our architecture improves QoS guarantee with lower delay and better throughput for real-time traffic without any reasonable overhead.

The rest of the paper is organized as follows. Section 2 surveys works related to QoS-provisioning in WMSNs. The newly proposed cross-layer approach for QoS-provisioning in WMSNs is highlighted in Section 3. In an approach to optimize the network layer QoS-routing, statistical modeling of QoS parameters is performed in Section 4. Subsequently, we prove that optimal QoS routing problem is NP-complete and provide a near-optimal MOGA-based solution. Then, our WMSN MAC algorithm for QoS is discussed in Section 5. The performance of this QoS-enabled MAC is also analyzed here by using suitable modeling techniques. Simulation results in Section 6 demonstrate the efficiency of our solutions in obtaining the desired application-specific QoS guarantee. Section 7 concludes the paper with pointers for future works.

2. Related Works in WMSNs and QoS

The work in [10] aims to overcome the weakness of traditional static WSNs by introducing a surveillance technology that can support intelligent mobile surveillance services. Research work in [11] designs a two-tiered system with the objective of reducing energy consumption with minimum loss in detection capability. Further extending on this, the authors in [12] propose a three-tiered system with distinct sensor nodes: PIR sensors for continuous sensing, smart visual camera sensors for object identification, and visual sensors for event-based operation.

Most of the potential applications of WMSNs require a new mechanism, which can deliver multimedia content at a certain level of QoS. Aside from minimizing energy consumption, mapping the content delivery requirements to network-layer metrics, like jitter and delay, is a major issue which presents a challenge to the implementation of WMSNs [13]. In order to overcome these problems, an image transport protocol is proposed in [14], which supports receiver-controlled reliability and out-of-order packet delivery. A double sliding window method is exploited in [15] to prevent packet loss between nodes. The authors in [16] apply a statistical reliability metric that prevents the number of data packets delivered to the sink from exceeding the defined threshold.

The major difference between WSNs and WMSNs, which makes the routing techniques for the former not directly applicable for the latter, arises from the stringent QoS requirements of underlying multimedia traffic. WSNs routing protocols mostly consider energy efficiency to be the main objective and therefore result in dissatisfactory performance, when applied on WMSNs [17]. However, a query-based and adaptable routing protocol for WSNs [18] can dynamically guarantee different QoS requirements, like latency and reliability, depending on the nature of the application. The work in [19] also presents a multi-path routing protocol, while considering heterogeneous traffic, which plans the shortest route for real-time constrained traffic and a longer route for non-time constrained traffic. A QoS-aware routing mechanism design specifically for WMSNs is proposed in [20], where the routing decision is made based on the dynamic adjustment of the required bandwidth. The authors in [21] study the energy-efficient multipath routing using joint-route construction, relay assignment and power allocation methods. Recently, protocols for specific application or circumstance are studied. In 2014, 54% of the world's population lives in urban areas and it is expected to grow to 66% by 2050 [22]. Therefore research works for “Smart Cities” are becoming indispensable. For smart cities, a new TDMA-based MAC protocol is proposed for improving the quality control of smart city applications [23]. It considers large number of small size time slots, which are more than the number of sensor nodes. Moreover, Knapsack optimization scheme is employed for scheduling time slots. For wireless clinical environment, hybrid periodic-random massive access technique is proposed in [24]. It can dynamically allocate the resources for periodic and random services to sensors, wearable devices and e-health monitoring devices. In [25], a novel movie recommendation system on the cloud platform is proposed by using multimedia big data analysis.

Cognitive technology selects the use of spectrums having the best propagation characteristics, thus reducing the power consumption and increasing the network lifetime. However, it also fetches additional challenges, like higher energy consumption, arising from sensing and switching of multiple spectrums, like Wi-Fi, Bluetooth and cellular radio. In order to increase energy efficiency, in [26], CR-WMSNs are split into a number of non-disjoint feasible subsets and only one subset operates at a time. Each subset is switched on successively, and other sensors remains in a sleep mode for increasing the network lifetime. In [27], CR-WMSN MAC protocol for supporting real-time traffic is proposed, which can access empty channels in the beginning of each channel switching intervals. There exists a handful of few research works in cross-layer optimization for WSNs. For smart grid application, a cross-layer framework based on the cognitive wireless is proposed [28]. It dynamically accesses available spectrum on the basis of signal interference, differentiates the traffic flow into different priority classes according to QoS constraints and transmits the data to maximize the bandwidth utilization. In [29], a cross-layer MAC and PHY optimization in introduced to minimize energy consumption. For medical systems, a cross-layer channel access and routing protocol is proposed in [30] to efficiently support medical-grade QoS packets. Motivated by these research works, we proposed a new cross-layer (Network and MAC) QoS framework for WMSNs. Our major new contribution lies in proposing novel interactions between sensory network and MAC layer, where the network layer provides (near) optimal QoS routes from a milti-objective perspective and the MAC layer uses this network layer QoS information, performs QoS-based congestion window adaptation for actual packet transmission.

As explained before, the emerging applications, like industrial automation, medical device monitoring, traffic monitoring and surveillance demand WMSNs to process and provide multimedia contents with a competent QoS. We believe that investigations in both network as well as MAC layers are needed to provide a satisfactory level of QoS in WMSNs. The objective of the MAC layer is to look after actual packet classification (e.g., real-time and non-real-time) and delivery. On the other hand, the network layer is responsible for discovering the QoS-enabled routes. This motivates us to search for efficient cross-layer algorithms for QoS-provisioning in WMSNs. In the next section we will give an outline of the newly proposed cross-layer QoS-provisioning architecture.

Table 1. Existing Literature of WMSNs

Reference	**Research Work**
WMSN Architecture	
[10]	- Surveillance technology to support intelligent mobile surveillance services
[11]	- Two-tiered system to reduce energy consumption

	- Separate imaging techniques for resource constrained sensors and actuated cameras
[12]	- Three-tiered system with distinct sensor nodes for environmental monitoring
Fulfilling QoS-stringent requirements of WMSN	
[14]	- Receiver-controlled reliability and out-of-order packet delivery - Synchronize local clock of all sensor nodes
[15]	- Double sliding window to prevent packet loss, comm. failure and network congestion
[16]	- Balance energy consumption and reliability
[18]	- Guarantee different QoS requirements depending on application - Ensure reliability using multiple paths and transmission of the same message
[19]	- Plan shortest route for real-time constrained traffic and longer route for non-time constrained traffic to reduce energy consumption
[20]	- Route based on dynamic adjustment of required bandwidth - Route real-time data according to path length based proportional delay differentiation - Maximize throughput of non-real-time-data by regulating data service rate
[21]	- Energy-efficient multi-path routing by relay assignment and power allocation - Heuristic algorithm to save power consumption and satisfy bandwidth
[23]	- TDMA-based MAC protocol for smart cities applications - Consider large number of small time slots with employ Knapsack optimization
[24]	- Hybrid periodic-random access technique for wireless clinical environment - Allocate dynamically the resources for periodic and random services
[26]	- Energy-efficient scheduling of each sensor active time - Divide sensor nodes into a number of non-disjoint feasible subsets
[27]	- Support real-time traffic - Access empty channels in the beginning of each channel switching intervals
[28]	- A cross-layer framework based on the cognitive concept in power systems - Differentiate traffic classfication to maximize bandwidth utilization
[29]	- A cross-layer optimization approach for PHY and MAC layers - Minimizing energy consumption by using optimizing FEC
[30]	- A cross-layer channel access and routing protocol for medical systems - Determine the routing path and allocate the QoS category to each packet

3. Cross-Layer QoS-Provisioning Architecture in WMSNs

Fig. 1(a) explains the flow chart of our proposed cross-layer QoS-provisioning architecture in WMSNs. The proposed framework can be split into two distinct parts for each flow in WMSNs. In the network and MAC layers, these two parts are activated. In this section, we describe our QoS-provisioning scheme with high-level discussion, by indicating the overview of activities and mutual interactions in the network and MAC layers. We explain details of these activities of the two individual layers in the subsequent sections. As shown in the upper-half of the **Fig. 1(a)**, the primary activities of network layer are as follows:

(1) The network layer is in charge of issuing the request for the setup of a flow.

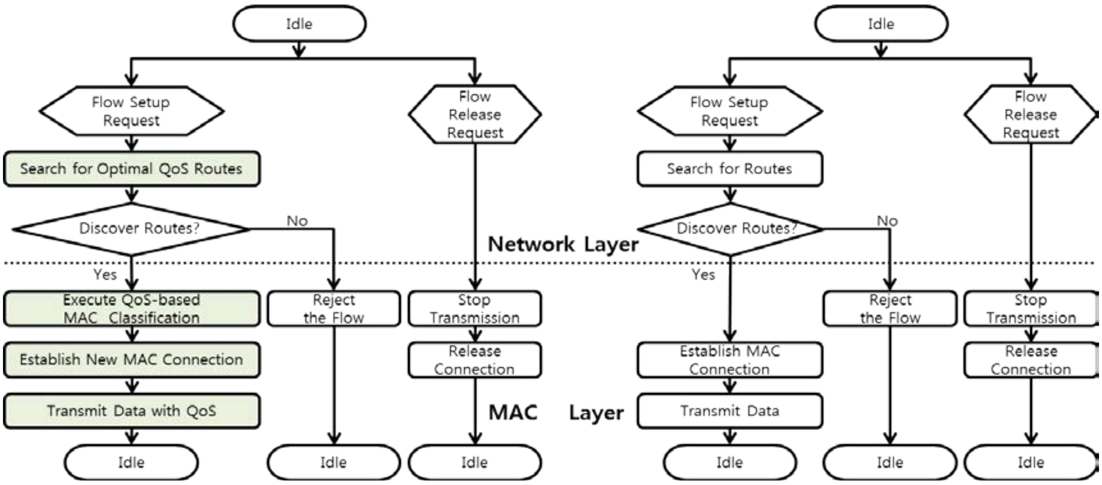
(2) It also discovers and searches the optimal QoS routes that guarantee a satisfactory level of QoS. Of course, the topology of the WMSNs could change, because of the depletion of the battery, malfunction of sensor node or any other external influences. Therefore, all flows influenced by topology change go into the setup and reconfiguration phase until a new route is set up. We explain this QoS-routing in Section 4.

(3) Now, the routes with guaranteed QoS parameters are determined by the network layer. This routing information is passed to the MAC layer for subsequent setup of MAC layer connections and delivery of actual packets.

(4) Finally, the network layer is also in charge of issuing the request for releasing of a flow.

As shown in the lower-half of the **Fig. 1(a)**, the major activities of WMSN MAC protocol in the MAC layer are:

(1) If the QoS-based route is discovered in the network layer, the WMSN MAC protocol classifies the packets according to the packet's Type-of-Service (ToS). Namely, different flows are distinguished according to ToS.
(2) Then the connection of MAC layer is established between the transmitter and receiver. We delineate the details of this QoS-based packet classification and MAC layer connection setup process in Section 5.
(3) Then in order to transmit the data frames, the routing information obtained by the network layer is used by the MAC layer.
(4) On the other hand, if the QoS-based routes cannot be discovered by the network layer, the WMSN MAC protocol rejects the corresponding flow by admission control. This means that the session or connection setup becomes un-successful.
(5) As soon as the MAC layer receives a flow release request from the network layer, it attempts to stop the data transmission and releases the flow.



(a) Proposed cross-layer QoS-provisioning architecture (b) Conventional architecture

Fig. 1. Cross-layer QoS-provisioning in WMSNs

It is anticipated that the time scale of delivering the data (e.g., packet per second) and changing the topology (e.g., change per hour) is significantly different. Therefore, every flow will spend a large portion of time in the transmission stage and relatively less time in the setup and reconfiguration stage. In the following two sections, the details of the above-mentioned QoS-based routing and QoS-classification scheme are explained.

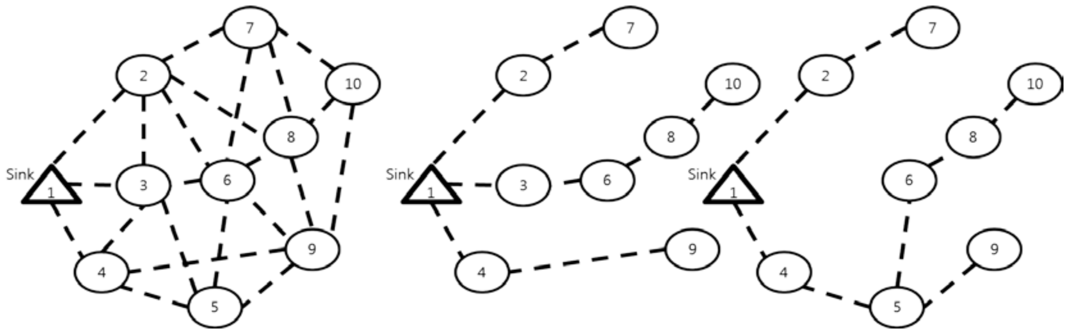
4. Towards Optimal QoS-Routing in WMSNs

As mentioned in Section 3, the primary objective of the QoS-routing in WMSNs is to discover the optimal route, satisfying the set of desired QoS requirements. In this section, we will explain a feasible method of statistical estimation of QoS parameters. We then discuss the complexity of obtaining the optimal QoS-route. Afterwards an efficient near-optimal algorithm for achieving a feasible solution is provided.

4.1 Statistical Modeling of Sensory QoS

The input WMSNs is represented by a graph $G = (V, E)$, where V and E respectively represent the set of nodes and the set of edges. A path between a source (v_s) and a destination (often termed as *sink*) (v_d) is delineated by a sequence of nodes $v_s, v_1, v_2, \dots, v_d$ where $v_i \in V$. Of course, multiple paths between source and destination pair might exist. The main goal in the WMSNs is to discover such paths between a group of sources and a sink, satisfying the specified QoS and energy constraints. Basically these paths form a tree topology and there might be multiple such trees for a given WMSNs.

For example, **Fig. 2(a)** depicts WMSNs that consist of 10 nodes with random connectivity. **Fig. 2(b)** demonstrates two plausible routing trees, made up of node 7, node 9, and node 10 as source nodes and node 1 as the sink. However, some of these tree routes might fail to satisfy the desired QoS and energy constraints. The underlying QoS routing attempts to find out a non-dominated paths, satisfying end-to-end delay, total bandwidth and energy remaining.



(a) Example of WMSNs (b) Two different routing trees with source = {7, 9, 10} and sink = 1

Fig. 2. A graph representing WMSNs

In order to deal with the uncertainty of wireless resources, the proposed scheme is designed to discover the paths by satisfying these objective parameters probabilistically. The network links are considered to be service queues, which are transmitting and servicing data packets. It is also assumed that the services offered by the network links are mutually independent. Even though the Poisson model is suited for estimating voice traffic, mostly it fails to represent the inherent Long-Range Dependency (LRD) of data traffic. In order to capture this LRD and heavy tail characteristic of data traffic, complex statistical analysis needs to be performed. Recently research works along this characteristic of data traffic have indicated the efficiency of Weibullian distribution [31] in modeling the data traffic with accuracy. Hence, our modeling of delay and bandwidth is based on Weibullian distribution.

(1) End-to-end delay: LRD of individual link delay is modeled by Weibullian distribution with average δ. Generally, the delay over a specific route from a source node to the sink is considered as the delay over the sequence of such links. Given a Weibullian distribution with a rate of change δ, the distribution function $\Theta(t)$, giving the delay until the kth Weibullian event, could be derived as:

$$\Theta(t) = 1 - \sum_{h=0}^{k-1} \frac{e^{-\delta(t/\phi)^{\psi}}\left[\delta(t/\phi)^{\psi}\right]^{h}}{h!} = 1 - \frac{\Gamma(k, t\delta\phi\psi)}{\Gamma(k)} \qquad \forall t \in [0, \dots, \infty) \tag{1}$$

$$\Rightarrow \Theta(t) = \frac{e^{-\delta(t/\phi)^{\psi}}\delta^{k}(t/\phi)^{\psi(k-1)}}{(k-1)!}, \tag{2}$$

where $\Gamma(x)$ and $\Gamma(x, y)$ are respectively complete and incomplete gamma functions. The constants ϕ and ψ are the scale and the shape parameter, respectively. Assuming the worst case, with all independent paths p, the probability that the delay (d_τ), along the selected path in the routing tree, τ , satisfying the specific delay constraint, is achieved as:

$$\Pr(d_\tau < t) = \prod_{p\in\tau} \Theta(t). \tag{3}$$

The first goal of the QoS-routing algorithm is to maximize this probability, $\Pr(d_\tau < t)$.

(2) Total bandwidth: The bandwidth on individual links also submits to Weibullian distribution. The probability with which the bandwidth requirement Υ is met in the routing tree τ is obtained by taking the product of distribution for the individual links:

$$Pr_k(\Upsilon) = \frac{e^{-\Upsilon(t/\Phi)^{\Psi}}[\Upsilon(t/\phi)^{\psi}]^k}{k!} = \prod_{k\in\tau} Pr_k(\Upsilon). \tag{4}$$

(3) Normalized energy remaining: For the sensor node, energy consumption can be calculated by using the energy consumed during data transmission $(\mathbb{E}_{tx})$ and reception $(\mathbb{E}_{rx})$. Thus, normalized energy remaining can be achieved as:

$$\mathbb{E}_{Remaining} = \frac{\mathbb{E}_{init}-(\mathbb{E}_{tx}+\mathbb{E}_{rx})}{\mathbb{E}_{init}} = \frac{\mathbb{E}_{init}-(e_{tx}+e_d r^{\alpha}+e_{rx})\mathfrak{B}}{\mathbb{E}_{init}} \tag{5}$$

where $\mathbb{E}_{init}$ is the initial energy. r is a transmission range and α $(2< \alpha <4)$ is a path-loss parameter. e_{tx} , e_d , e_{rx} represent the unit-energy (energy/bit) used by transmitter, operational amplifier and receiver electronics, respectively. $\mathfrak{B}$ is the traffic bit-rate that is a factor of bandwidth Υ.

The objective of optimal QoS-routing in WMSNs is to maximize $\Pr(d_\tau < t)$, $\Pr_\tau(\Upsilon)$ and $\mathbb{E}_{Remaining}$ simultaneously, as discussed in Equation (3), Equation (4) and Equation (5). Formally, we can state the optimization problem as follows:

$$\mathrm{OPT} = \max[\Pr(d_\tau < t), Pr_\tau(\Upsilon), \mathbb{E}_{Remaining}]. \tag{6}$$

As QoS-routing problem with multiple objectives is proved to be NP-complete [32], we claim that the maximization problem mentioned above is also NP-complete. In the subsequent parts of this section, near-optimal solution of this NP-complete problem within computationally feasible time is attained by using multi-objective genetic algorithm as our optimization technique.

4.2 Basics of Multi-Objective Genetic Algorithms

It is clear that NP-complete problems are basically of exponential order, i.e. $O(2^n)$. Therefore, NP-complete problem cannot be solved in polynomial time, i.e. computationally feasible time. Thus, in order to achieve a near-optimal solution in polynomial time, searching for an efficient heuristic algorithm is the realistic and reasonable way. It is well known that genetic algorithms are one kind of random search and heuristic algorithms, based on the basic principles of natural evolution: *"survival of the fittest"* and *inheritance* [33]. Genetic algorithms imitate the natural evolution process through crossover, selection and mutation operations [33]. In order to solve an optimization problem, genetic algorithms basically carry out five major operations: (a) Mapping the solution-space of a problem to a set of strings (chromosomes), termed as *population*; (b) *fitness evaluation* - decoding each string in order to assess its value; (c) *selection* - copying the parent strings into a temporary new population mating pool (d) *crossover* - information exchange between two randomly selected parent strings in order to give a birth to offspring strings; (e) random reconstruction of the string structure for exploring diversity and escaping from any local optimal points. When every iteration (generation) is performed, this operation enhances the quality of the solution strings like the biological evolution. Ultimately, very near-optimal solution can be obtained in computationally feasible time.

However, the optimization of multiple objectives is simultaneously required in various real world problems. This fairly differs from the optimization of a single objective. There may be a set of solutions, better than the rest with respect to all the objectives under consideration. Such a set of solutions is called as *Pareto-optimal* [34]. An approach to MOGA [35] gets out from ordinary genetic algorithms only in its selection operation. Before MOGA performs the selection, the population is ranked based upon non-domination of individual string, i.e. the string-set better than the rest while considering all the parameters. The initial *Pareto-optimal* front is composed of such non-dominated strings [34]. At every iteration, the non-dominated Pareto-optimal solutions are obtained. Then, in order to improve their fitness values, genetic operations are executed on them. If we view the set of QoS-routes as the strings, the outcome fittest string in the whole search space will represent the optimal QoS-route in the WMSNs. In the next subsection, we explain more details about this.

4.3 Near-Optimal QoS-Routing in WMSNs

WMSN QoS-routing algorithm, as mentioned in **Fig. 1(a)** of Section 3, attempts to obtain the optimal QoS-routes. The fundamental idea behind this cross-layer QoS-provisioning algorithm is not to integrate the specific QoS and energy-based objective functions, on ad hoc basis, to formulate a single objective function; but to deal with the problem with a multi-objective optimization point of view. The motivation of our routing algorithm is to offer the user with a set of Pareto-optimal solutions and give him a chance to select the best possible solution from this set, according to the specific QoS requirements.

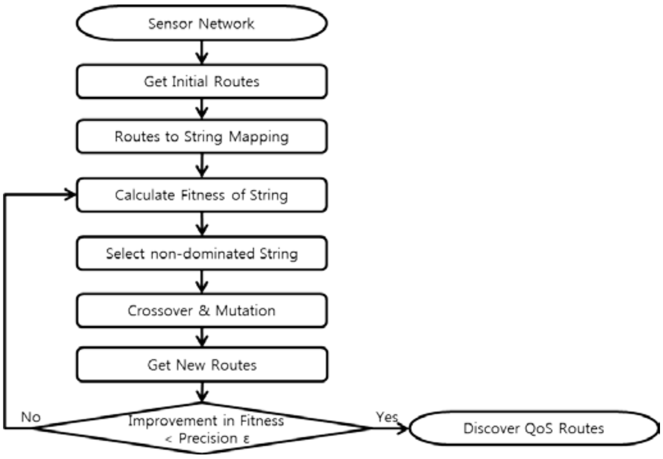


Fig. 3. Near-optimal QoS-routing algorithm

Fig. 3 shows the flow chart of our algorithm. Note that, the procedure in **Fig. 3** is actually abstracted inside the "Search for Optimal QoS Routes" block of **Fig. 1(a)**. An input network $\mathrm{G} = (\mathrm{V}, \mathrm{E})$, a specific number of source nodes $v_1, v_2, \dots, v_{s_n}$ and a single destination (sink) v_d is taken by the algorithm. Then, a pool of possible routing paths from v_d to each of $v_1, v_2, \dots, v_{s_n}$ is found by the routing algorithm, by using a Depth First Search (DFS). This gives the initial set of routing trees. Each routing tree is a mapping to a string, which is composed of the sequence of nodes along the path from v_d towards each of the destinations $v_1, v_2, \dots, v_{s_n}$. The set of all these initial strings is regarded as the initial population of chromosomes for the proposed MOGA.

The fitness value of a string is calculated with the help of above three estimated parameters. The objective of our proposed algorithm is summarized to a search for different routing paths that will increase the values of the QoS parameters at each iteration. In order to generate a comparison set, a certain number of strings are randomly selected from the population. From the population, two strings are randomly chosen and compared with each string in the comparison set. If one candidate string is better than competitors considering all three QoS parameters, then *Pareto-Optimal* [34], [35] set contains this string. On the other hand, if both the competitors are non-dominated, then a niche count [34], [35] is used to resolve this tie situation. Niche count is estimated as mentioned in [34], [35]:

$$m_i = \sum_{j=1}^{pop\ size} S\left[d_{s_i,s_j}\right], \tag{7}$$

where $S\left[d_{s_i,s_j}\right]$ is the sharing function and d_{s_i,s_j} is the distance between the strings s_1 and s_2. A triangular sharing function [34] is used as:

$$S\left[d_{s_i,s_j}\right] = \left|1 - \frac{[(\Delta_{delay_{s_i,s_j}})^2 + (\Delta_{bw_{s_i,s_j}})^2]^{1/2}}{\frac{1}{2} \times [(\Delta_{delay_{max}})^2 + (\Delta_{bw_{max}})^2]^{1/2}}\right|, \tag{8}$$

where $\Delta_{\mathrm{delay_{max}}} = \mathrm{Pr_{max}}(\mathrm{d}_\tau < \mathrm{t}) - \mathrm{Pr_{min}}(\mathrm{d}_\tau < \mathrm{t})$, $\Delta_{\mathrm{bw_{max}}} = \mathrm{Pr_{max}}(\Upsilon) - \mathrm{Pr_{min}}(\Upsilon)$ and $|(\mathrm{x} - \mathrm{y})|$ represents the difference between x and y. In order to mix the good strings and protect the effective ones simultaneously, the probability of crossover and mutation are considered as 0.8 and 0.1 respectively. This entire process is repeated until the improvement in fitness values (from previous to current Pareto-optimal set) is less than a chosen precision, ε. Actual precision value (ε) will be distinct according to corresponding QoS parameters. 10^{-6}, 10^{-5} and 10^{-3} are chosen as the precision values for the probabilities of end-to-end delay, total bandwidth and energy remaining, respectively. Finally, the strategy returns the results of the discovered QoS-route (whether success or failure and the set of routes) to the cross-layer QoS-provisioning algorithm shown in **Fig. 1(a)**.

For a set of $\mathcal{M}$ sensor nodes, the complexity of our proposed QoS routing algorithm could be estimated in a step-by-step manner as follow:

(1) The initial routs estimation using DFS and routes to string mapping could be performed with a complexity of $\mathrm{O}(\mathcal{M})$. This results in obtaining the initial subset of $\mathcal{M}'$ sensor nodes, where $\mathcal{M}' < \mathcal{M}$.

(2) The fitness functions are estimated with a complexity of $\mathrm{O}(\mathcal{M}')$.

(3) The non-dominated sorting could be performed with a complexity of $\mathrm{O}(\mathcal{M}' \log \mathcal{M}')$, using heapsort.

(4) Genetic operations, like crossover and mutations to achieve new solutions require

$O(\mathcal{M'}^2 \log \mathcal{M'})$ in the worst case [36].

(5) Finally, the step 2~4 are repeated a finite number of times ($\mathcal{J}$), until the improvement in less than chosen precision, ε.

(6) Thus, the overall complexity of the algorithm is bounded by $O(\mathcal{J}\mathcal{M'}^2 \log \mathcal{M'})$. As, typically for a huge set of sensor nodes, $\mathcal{J} \ll \mathcal{M}$ and $\mathcal{M'} < \mathcal{M}$, we can say that the complexity $O\left(\mathcal{J}\mathcal{M'}^2 \log \mathcal{M'}\right) < O(\mathcal{M}^3 \log \mathcal{M})$.

Note that the similar existing work by Deng et. al. [26] discusses three different approaches Implicit Enumeration (IE), Generic Greedy (GG), λ Greedy (λG). While IE approach provides optimal solution at the cost of exponentially high complexity, GG solution provides poor optimization results with $O(\mathcal{M} \log \mathcal{M})$ complexity. On the other hand, the λG method provides a near-optimal solution with a reasonable $O(\mathcal{M}^3 \log \mathcal{M})$ complexity. Thus, we can say that comparing to existing work [26], our QoS routing strategy offers a near optimal solution with a relatively lower complexity.

5. MAC Protocol for QoS IN WMSNs

While the QoS-routing solution explained in Section 4 makes an attempt to discover near-optimal routes meeting the QoS-requirements, the MAC layer is in charge of the classification and transmission of data packets. Hence, in order to satisfy the complete QoS requirements, the WMSN MAC protocol also needs to be aware of QoS. Since CSMA-MAC methods provide a lower delay and better throughput [37], especially at light traffic loads, the CSMA schemes similar to IEEE 802.11 are explored for the proposed QoS MAC protocol in WMSNs.

5.1 QoS in WMSNs

In this subsection, we introduce a new contention window (ω) adaption scheme in CSMA-CA to develop our QoS-based MAC protocol. The proposed QoS-based WMSN MAC protocol in WMSNs is based on monitoring the sensor-dynamics at every t seconds and obtaining the relevant network statistics, in other words the number of total transmission success (ζ_s) and transmission failure (ζ_f). On the basis of these values, the probability of transmission failure (Pr_f) is calculated empirically by our protocol. Then, this probability is used to update the MAC parameters, such as contention window for the particular sensory node. Pr_f represents the probability of transmission failure due to collision among the total trials to transmit packets and is mathematically represented as $Pr_f = \frac{\zeta_f}{\zeta_f + \zeta_s}$.

5.1.1 QoS MAC Protocol

After performing the near-optimal QoS routing, the cross-layer framework, mentioned in **Fig. 1(a)**, calls out the QoS MAC strategy to allocate the channel resources efficiently. Our proposed MAC algorithm updates and adjusts the ω to obtain the tradeoff between two points: (a) the waiting period for the expiry of back-off counter and (b) the collision arising from concurrent transmissions. Afterwards, it classifies the packets according to traffic type and updates the ω in different amounts. We now discuss proposed QoS MAC strategy:

(1) For after every t seconds the QoS-based MAC algorithm checks the number of transmitted packets and goes to the next stage only if more than ϱ packets are transmitted.

(2) In the next stage, the QoS-based MAC algorithm estimates the current probability of

transmission failure ($\mathrm{Pr_f}(\mathrm{t})$) by using the number of transmission successes and failures.

(3) The sensor node that grows its ω should statistically see reduced $\mathrm{Pr_f}(\mathrm{t})$ if all other nodes in the same traffic type also perform the same process. On the other hand, if the sensor node actually sees grown $\mathrm{Pr_f}$ in the next round, this represents that the other WMSN nodes does not grow ω. In this situation, the victim node should maintain the ω in this round and repose the time for other sensor nodes to update their individual ω. Reduction in ω results in similar impacts and consequences. As a result, some stability can be maintained statistically in a stop-for-a-round fashion.

(4) The general concept of CSMA-CA-based MAC protocol announces that large $\mathrm{Pr_f}$ corresponds large ω and small $\mathrm{Pr_f}$ corresponds small ω. Therefore, $\mathrm{Pr_f}$ can be mapped to the target ω, which guides the direction of ω adjustment. The target (ω_{target}) and present contention window (ω_{cur}) together determine the actual step size, according to the following equation:

$$\Delta\omega = \xi \times \frac{\omega_{target} - \omega_{cur}}{\omega_{cur}}, \qquad \omega_{cur} = \omega_{cur} + \Delta\omega \tag{9}$$

where ξ is the QoS-based scaling factor. This indicates that the larger the difference between ω_{target} and ω_{cur} becomes, the larger the step size will become, and vice versa.

At the end of this process, an adaptive MAC contention window is generated according to the traffic types and the sensor nodes access the channel by using this contention window. After the MAC connection is set up, the control is transferred to the cross-layer QoS-provisioning algorithm mentioned in **Fig. 1(a)**.

5.1.2 Traffic Type Discrimination

The scaling factor ξ is decoupled into ξ_{up} (up scale) and ξ_{down} (down scale), for growing and reducing ω respectively. The ξ_{up} of traffic types with higher priority (like video streaming) is set to be smaller than that of lower priority; instead, the ξ_{down} is set to be greater than that of lower priority. ξ_{down} could be estimated as negative of ξ_{up}. Thus if ascending indexes indicate descending priorities, then $\xi_{up}(1) < \xi_{up}(2) < \cdots < \xi_{up}(n)$ and $\xi_{down}(1) > \xi_{down}(2) > \cdots > \xi_{down}(n)$. While supporting the discrimination, the mapping function is designed to be monotonically increasing over (Pr_f^{lower}, ω_{min}) and (Pr_f^{upper}, ω_{max}). The ω_{min} and ω_{max} of higher priority traffic types is set to be smaller than those of lower priority traffic types.

5.2 Modeling and Queuing Analysis

Different traffic classes are decoupled into different categories, with their own parameters, like Maximum and Minimum Contention Window (ω_{min}, ω_{max}) and Inter-frame Space (IFS). The sensor nodes can be considered as a collection of priority queues. The packet arrival at any node *i* follow a Poisson process with rate λ_i. By using available WMSN bandwidth and packet lengths, this arrival rate λ_i can be estimated. On the other hand, the delivery of packets is up to the packet-priorities, getting from the ToS associated with each traffic type.

The sensor nodes constantly perceive the wireless channel using a CSMA-CA approach and nodes can lie in one of the three states: (a) empty (b) successful transmission or (c) collision. For any sensor *i*, the probabilities of empty ($p_{(e,i)}$), success ($p_{(s,i)}$) and collision

($p_{(c,i)}$) could be estimated by using the stationary transmission probabilities (π_j) of all other n-1 nodes:

$$p_{(e,i)} = \prod_{j\neq i}(1-\pi_j),\quad p_{(s,i)} = \sum_{z\neq i}\pi_z \prod_{j\neq z\neq i}(1-\pi_j),\quad p_{(c,i)} = \left[1-p_{(e,i)}-p_{(s,i)}\right]. \qquad (10)$$

Only when after sensing that the channel is free for one slot (σ), the back-off counter can be decreased. Therefore, the time between two consecutive declines of back-off counter is a channel-dependent stochastic random variable. Hence, it can be estimated as follows:

$$\lambda_i = \sigma p_{(e,i)} + \left(E\left[t_{(s,i)}\right]+\sigma\right)p_{(e,i)} + \left(E\left[t_{(c,i)}\right]+\sigma\right)p_{(c,i)}, \qquad (11)$$

where $E\left[t_{(s,i)}\right]$ stands for the expected duration of a successful transmission and $E\left[t_{(c,i)}\right]$ represents the that of collision. Fundamentally these channel duration depends on packet lengths, number of packets and traffic types (i.e., ToS). Surely, the use of higher priority packets will occupy the wireless channel more by the corresponding node. The probability that a WMSN node S_i transmits the data in a random selected slot π_i, is up to (a) S_i has data to be transmitted (b) the parameters of traffic type of S_i and (c) the action of other WMSN nodes. This can be represented as:

$$\pi_i = \frac{\rho_i}{1+BO+IFS}, \qquad (12)$$

where ρ_i denotes the overall occupancy of the WMSN node S_i. BO and IFS represents the slots associated with the binary exponential back-off and the inter frame space, respectively. The probability that a WMSN node $S_{k\neq i}$ transmits the data while the WMSN node S_i lies in back off is calculated as: $1-\prod_{j\neq i}(1-\pi_j)$.

5.3 Average Waiting Time Estimation

We assume that the video streaming traffic has the highest priority and the Best Effort (BE) data traffic has the lowest priority. In this subsection we will analyze the average waiting time, which is induced in each of traffic types. For type *i* customer, $E(\overline{\mathfrak{I}_\iota})$ is the average waiting time and $E(N_i^q)$ is the number of type *i* customers waiting in the queue. It is also assumed that the processing time of traffic class *i* as μ_i with mean $E(\mu_i)$ and residual processing time as $\mathfrak{R}_i$ with mean $E(\mathfrak{R}_i)$. The traffic intensity of the system is then estimated as: $\rho_i = \lambda_i E(\mu_i)$ [31]. Therefore, for real-time streaming traffic with the highest priority, it holds that

$$E\left(\overline{\mathfrak{I}_1}\right) = E\left(N_1^q\right)E(\mu_1) + \sum_{j=1}^{r}\rho_j E(\mathfrak{R}_j) = \frac{\sum_{j=1}^{\mathfrak{R}}\rho_j E(\mathfrak{R}_j)}{1-\rho_1}. \qquad (13)$$

For the lower priority traffic, it is more complicated to determine the average waiting time. The waiting time of a type *i* customer ($\forall i > 1$) can be partitioned into some portions. The first portion, called portion $\mathfrak{I}_1$, is the amount of the work related to the serviced traffic and all customers with the same or higher priority exist in the queue upon this arrival. The second portion, called portion $\mathfrak{I}_2$, is the amount of the higher priority work which is arriving during portion $\mathfrak{I}_1$. Thence the third portion, called portion $\mathfrak{I}_3$, is the amount of the higher priority work which is arriving during portion $\mathfrak{I}_2$, and so on. We can thus say that:

$$\mathrm{E}(\mathfrak{I}_1) = \sum_{j=1}^{i} \mathrm{E}\left(N_j^q\right)\mathrm{E}\left(\mu_j\right) + \sum_{j=1}^{r} \rho_j \mathrm{E}(\mathfrak{R}_j). \tag{14}$$

Since $\mathfrak{I}_{k+1}$ depends on $\mathfrak{I}_k$, estimating $\mathrm{E}(\mathfrak{I}_{k+1})$ needs conditioning on the length of $\mathfrak{I}_k$. Therefore, expressing the pdf of $\mathfrak{I}_k$ by $f_k(x)$, we can explain as follows:

$$\begin{aligned}\mathrm{E}(\mathfrak{I}_{k+1}) &= \int_{x=0}^{\infty} E(\mathfrak{I}_{k+1}|\mathfrak{I}_k = x) f_k(x)dx = \int_{x=0}^{\infty} (x \sum_{j=1}^{i-1} \lambda_i E(\mu_i))\, f_k(x)dx \\ &= (\rho_1 + \cdots + \rho_{i-1}) E(\mathfrak{I}_k) = (\rho_1 + \cdots + \rho_{i-1})^k E(\mathfrak{I}_1).\end{aligned} \tag{15}$$

Hence, the average waiting time for lower priority traffic at every WMSN node is estimated as follows:

$$\mathrm{E}\left(\overline{\mathfrak{I}_\iota}\right) = \frac{\sum_{j=1}^{i} \mathrm{E}\left(N_j^q\right)\mathrm{E}\left(\mu_j\right) + \sum_{j=1}^{r} \rho_j \mathrm{E}(\mathfrak{R}_j)}{1-(\rho_1+\cdots+\rho_{i-1})}, \tag{16}$$

$\forall i \in [2, n]$. Average behavior for different traffic types in the proposed QoS-based MAC protocol is provided from Equations (13) to (16). The average waiting time for different traffic types can be achieved by putting $i = \{2,3,4, \dots, n\}$.

6. Simulation Experiments and Results

In this section we first explain our simulation framework for assessing the performance of our proposed QoS-based WMSN routing protocol. Afterwards we describe different simulation results representing the efficiency of the proposed QoS-based MAC protocol.

6.1 Simulation Framework

Our WMSNs simulator has been developed based on OPNET. Before discussing the simulation results, we would like to adress assumptions and major parameters:

(1) OPNET simulator is used to generate 100 sensor nodes for WMSNs. Initially, the connectivity of the WMSNs is kept at 0.7. The capacity of the network links is assumed to be a Poisson distribution with mean 100 kbps. Every sensor is assumed to have a small buffer of 5 Kbytes [38] [39]. Source node is selected at random.

(2) In order to include different traffic types, we have carried out our simulation with three different types of traffic, i.e. three flows. The video streaming traffic is considered to have 176 × 144 pixel resolution and an average exponential inter-arrival with 10 frames/sec as specified with H.264. The Non-Real-Time (NRT, e.g., file download with minimum reserved rate) and Best Effort (BE, e.g., E-mail or Hypertext Transport Protocol) data traffic are assumed to be long range Pareto distribution with heavy tails. The total size of files for NRT and BE data traffic are taken same as the overall size for video traffic.

(3) The classification of traffic is performed based on the ToS field of IP packets. ξ is kept

proportional to the IP-ToS. The up scaling factor ξ_{up} and down scaling factor ξ_{down} are considered as follows: (a) $\xi_{\mathrm{up}} = 20$ and $\xi_{\mathrm{down}} = 20$ for video streaming (b) $\xi_{\mathrm{up}} = 20\sqrt{2}$ and $\xi_{\mathrm{down}} = 10\sqrt{2}$ for NRT traffic and (c) $\xi_{\mathrm{up}} = 40$ and $\xi_{\mathrm{down}} = 10$ for BE traffic. The active time for video streaming traffic and NRT traffic are taken as 4 and 2 times of the active time for BE traffic, respectively.

(4) In our simulation ω_{min} and ω_{max} are taken to be 64 and 128 for BE traffic respectively, which corresponds to $\mathrm{Pr}_{\mathrm{f}}^{\mathrm{lower}} = 0.05$ and $\mathrm{Pr}_{\mathrm{f}}^{\mathrm{upper}} = 0.40$. We have set the corresponding values for the video streaming traffic to be 25% of the BE traffic.

(5) We repeat the simulation 100 times with 4 different network connectivity 0.5, 0.6, 0.7 and 0.8. The average values across all the runs with 99% confidence interval are reported. As shown in **Fig. 4**, for $\varrho(\text{the number of initial packets}) \geq 50$, the system reaches ω_{target} within 90 seconds. Thus, we have chosen $\varrho \geq 50$ for our experiments.

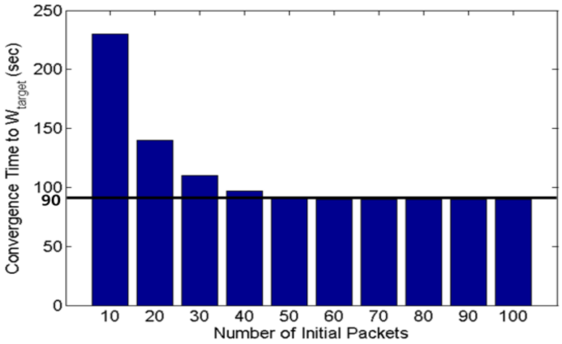


Fig. 4. Convergence time to $\boldsymbol{\omega_{target}}$

(6) The performance of our algorithm is compared with the related works of Deng et. al. [26] and Liang et. al. [27].

Table 2. Simulation Parameters

Parameter	Value	Parameter	Value		
Number of sensor node	100		Video	NRT	BE
Buffer size	5 Kbytes				
Network link capacity	Poisson (100 kbps)	ξ_{up}	20	$20\sqrt{2}$	40
Connectivity	0.5, 0.6, 0.7, 0.8	ξ_{down}	20	$10\sqrt{2}$	10
Video resolution	176 × 144 pixel	ω_{min}	16	32	64
Videl arrival rate	Exponential (10 frame/s)	ω_{max}	32	64	128

6.2 Performance Results

In this subsection, we evaluate the performance of our cross-layer framework. Subsequently, in the next subsection, we compare the performance of our solution with existing works [26] [27].

Fig. 5 shows how the Pareto-optimal QoS-probabilities are developed and moved forward to the global optimal probability in a reasonable time. Our algorithm can achieve the near-optimal values (probabilities of more than 0.90) of end-to-end delay, total bandwidth and energy remaining by building the non-dominated fronts, which is the novelty of our algorithm. From this figure, the percentage of global optimization achieved by the proposed algorithm can be derived for the given three parameters. Note that, WMSNs routes, which are not the best solution from a single QoS-objective perspective, might also be included in the solution set, as the solution set is non-dominated and provides a fair negotiation between both the objectives.

Fig. 6 explains that the execution time of our cross-layer algorithms, even with 500 sensor nodes, take only within 182 seconds. It means that, although the QoS optimization problem is NP-complete, proposed crosslayer algorithm solves the QoS-provisioning problem within a feasible time.

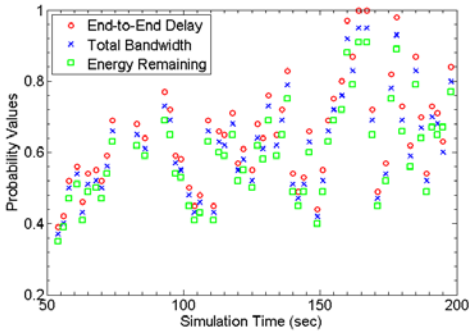


Fig. 5. Pareto-optimal QoS-probabilities

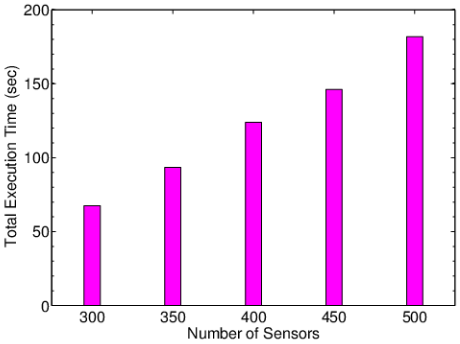


Fig. 6. Simulation execution time

Fig. 7 demonstrates the performance of MAC throughput for different traffic types. Our newly proposed WMSN MAC protocol first divides the traffic into different types according to the ToS fields. Afterwards, contention windows are adaptively adjusted according to the traffic types. This is the novelty of our protocol. Highest priority is assigned to the video streaming traffic, thereby making its ω the lowest (25% of the BE traffic). NRT traffic has the second priority, with 50% ω of the BE traffic. As depicted in **Fig. 7**, the video streaming traffic attains about 53.4 kbps median throughput (i.e., 50th percentile of throughput) and NRT traffic attains about 33.6 kbps median throughput. The BE traffic obtains the lowest median throughput of 12.9 kbps. By adjusting ξ_{up} and ξ_{down}, this throughout discrimination between traffic types can be easily managed as mentioned in Section 5.1.2. If you want to increase the throughput of video streaming traffic at the cost of the throughput degradation of NRT and BE traffic, you can decrease the value of ξ_{up} and increase the value of ξ_{down}. This is represented in **Fig. 8**, where the video streaming traffic attains about 78.9 kbps median throughput at the cost of NRT and BE throughput of 14.5 kbps and 6.2 kbps respectively.

On the other hand, **Fig. 9** shows the dynamics of MAC throughput for different traffic types in accordance with the presence and absence of video streaming traffic. Until 12 minutes the median throughput of video streaming, NRT and BE traffic are about 48.5 kbps, 27.0 kbps and 18.5 kbps respectively. Then, the video streaming traffic is absent in the interval [12, 22] minutes. At this interval the throughput of video streaming traffic is zero and the throughput of lower priority NRT and BE traffic increase to almost 52 kbps and 36 kbps respectively. However, after 26 minutes, as the video streaming traffic is again serviced, it immediately re-obtains about 56.5 kbps median throughput and the median throughput of lower priority NRT and BE traffic decrease to about 22.0 kbps and 15.5 kbps respectively. This also indicates the dynamic utilization of wireless channel with traffic dynamics of proposed QoS-based MAC protocol.

Fig. 10 explains the delay offered by our proposed WMSN MAC protocol for different traffic types. Video streaming traffic suffers lower median delay (i.e., 50th percentile of delay) of 23.3 milliseconds because of the lower contention window. The corresponding median delays related to NRT and BE traffic are about 39.8 and 60.0 milliseconds respectively. Classifying the traffic into different types and subsequently adjusting contention window according to traffic types assist in reducing delay for multimedia traffic with higher priority to quite low delay. Therefore, multimedia traffic with higher priority over WMSNs can be served with fine QoS.

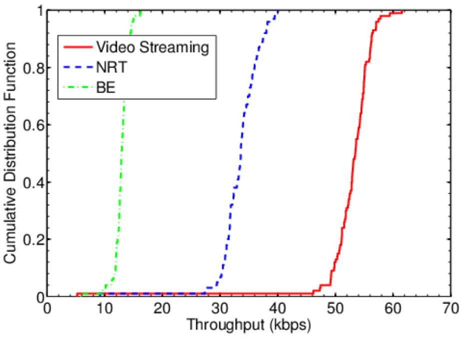


Fig. 7. MAC throughput discrimination

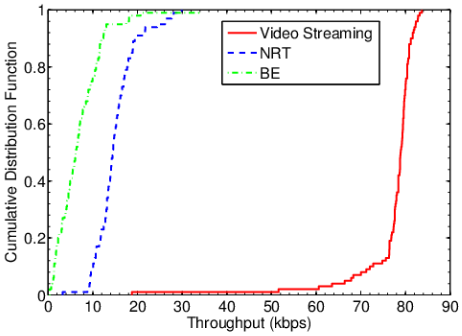


Fig. 8. MAC throughput tradeoff

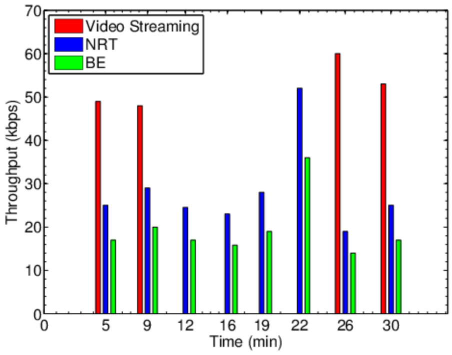


Fig. 9. Dynamics of MAC throughput

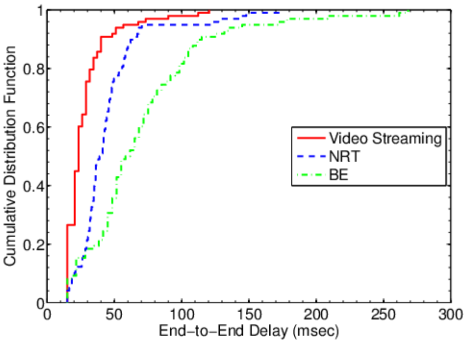


Fig. 10. Different traffic delays

Table 3 explains the tradeoff between delay and overall energy consumption offered by our QoS-based WMSN MAC protocol. For a quite low delay about 10 milliseconds, the energy consumption offered by our protocol is 28 mWHr. However, if a comparatively high delay, more than about 25 milliseconds is granted, the energy consumption reduces to less than 15 mWHr. It indicates that our QoS-based WMSN MAC protocol is able to manage the tradeoff between delay for multimedia traffic and sensory energy consumption.

Table 3. Delay VS. Energy Tradeoff

Case	End-to-End Delay (msec)	Energy Consumption (mWHr)	Case	End-to-End Delay (msec)	Energy Consumption (mWHr)
1	10	28	4	19	20
2	13	24	5	22	17
3	16	23	6	25	15

6.3 Performance Comparison

In this subsection, we generate the video streaming traffic and NRT traffic on a fifty-fifty basis for comparison. **Fig. 11** explains the comparison of delay for video streaming traffic offered by our protocol, Deng et. al. [26] and Liang et. al. [27]. It is quite clear that the proposed MAC protocol significantly outperforms both the protocols.

Fig. 12 shows the comparison between our protocol, Deng et. al. [26] and Liang et. al. [17] in terms of wireless throughput. While Deng et. al. [26] and Liang et. al. [27] achieves the median throughput of 16.1 kbps and 10.6 kbps respectively; our protocol achieves the median throughput of 23.5 kbps. Classifying the traffic into different types and subsequently adjusting contention window according to traffic types assist to estimate the wireless channel more precisely, than Deng et. al. [26] and Liang et. al. [27]. This improves throughput and delay performances.

Note that, even though the primary objective of the proposed MAC protocol is delivering the multimedia service with a competent QoS over WMSNs, it also tries to save the energy of sensor nodes by adjusting the duty cycle differently. **Fig. 13** depicts the comparative energy consumption of sensor nodes for our protocol, Deng et. al. [26] and Liang et. al. [27]. It is clear that when the packet arrival rate is increased, our proposed WMSN protocol achieves more energy saving than Deng et. al. [26] and Liang et. al. [27]. Finally, the comparison between simulated and analytical queueing delay of video streaming traffic, attained by using Equation **(16)** is delineated in **Fig. 14**. The simulation results closely correspond with the analytical results with a less than 5 milliseconds difference.

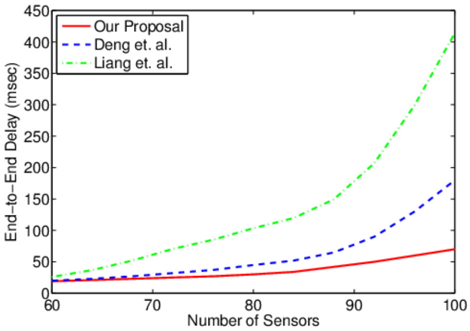


Fig. 11. Comparison of delay

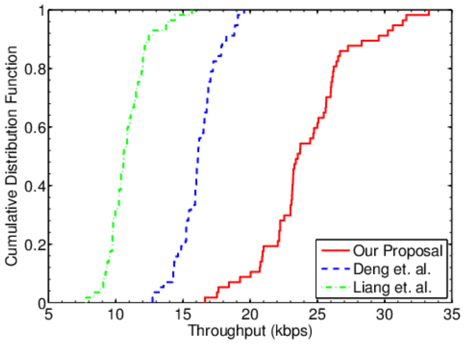


Fig. 12. Comparison of wireless throughput

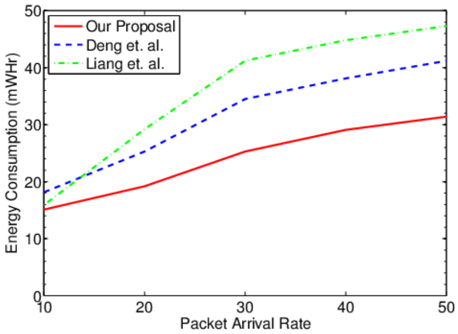


Fig. 13. Comparison of Energy consumption

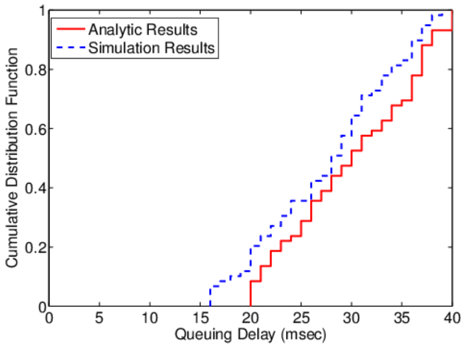


Fig. 14. Analytical and simulation results

7. Conclusion

As emerging applications require real-time data transmission, the paradigm of WSNs is enlarged to ensure QoS of multimedia contents. In this paper, we have proposed a new cross-layer QoS-provisioning architecture for efficient wireless multimedia transmission over battery constrained WMSNs. The network layer attempts to make statistical estimation of major QoS parameters and discover the near-optimal routes with specific QoS requirements by using genetic algorithms. The MAC layer, on the other hand, performs packet classification and contention window adaptation to actually deliver the real-time data packets. Our future works lie in investigating into efficient data fusion and localization schemes to integrate with this QoS-based WMSN framework. In the future, we would like to implement into Linux based development boards to enable real world testing.

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