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QoS in Wireless Multimedia Sensor Networks: A Layered and Cross-Layered Approach

Zara Hamid · Faisal Bashir Hussain

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Abstract The emergence of wireless multimedia sensor networks (WMSN) has given birth to several civilian as well as defense applications. Some of the interesting applications employing low cost sensor nodes to manipulate rich multimedia content include traffic monitoring, border surveillance, smart homes, environment and habitat monitoring. Unlike the traditional sensor networks which are aimed at maximizing network lifetime by decreasing energy utilization, the main objective of WMSNs is optimized delivery of multimedia content along with energy efficiency. Multimedia communications in WMSNs, has stringent delay and high bandwidth requirement as compared to scalar data transfer in WSNs. Fulfilling these constraints in resource and energy constrained WMSNs is a huge challenge. In WMSNs, each layer of the protocol stack is responsible and fully involved in providing QoS guarantees. There is a need for new schemes at each layer of the protocol stack- from advanced coding techniques that reduce encoder complexity and achieve maximum compression to dynamic routing and MAC protocols that provide service differentiation and reduce end-to-end latency. In wireless sensor networks, where all layers have dependency on each other, QoS guarantees are possible through the cross layer interaction of different layers. This paper gives an overview of the different existing layered schemes in WMSNs, followed by a discussion on the significance and efficiency gains that can be achieved from cross layer interactions in WMSNs along with the review of the existing cross layer approaches. Finally, we identify the open research issues which have not been adequately addressed so far.

Keywords Wireless multimedia sensor networks · Cross layer design · QoS

Z. Hamid (✉)
Department of Computer Software Engineering, National University of Sciences and Technology (NUST),
Islamabad, Pakistan
e-mail: xarahamid@yahoo.com; zara@mcs.edu.pk

F. B. Hussain
Department of Computer Science, Bahria University,
Islamabad, Pakistan
e-mail: faisalwn@yahoo.com

1 Introduction

The last decade has witnessed vast amount of research in traditional wireless sensor networks (WSN). WSNs are application specific networks that are designed according to the objectives and requirements of different applications. Due to the ability of these networks to be easily incorporated into any field, they have been continuously gaining popularity amongst researchers in all fields of life. Tiny sensor nodes have been deployed in hospitals, forests, mountains, glaciers, class rooms, caves and even in sporting events to gather and disseminate information. As useful and important as these networks are, they have severe resource and energy constraints. The concentration of research in WSN has been largely on minimizing energy consumption, query optimization, localization, data aggregation, coverage and network lifetime maximization. There have been several surveys on WSNs [1,2] highlighting their architecture, applications and challenges existing at each layer.

The introduction of low resolution, CMOS cameras and microphones, over low power, low cost nodes has given birth to WMSNs. This has opened doors to many possibilities of capturing multimedia content for applications in telemedicine, traffic monitoring, surveillance, intrusion detection and environment monitoring. The use of multimedia content dictates maintenance of QoS guarantees in these networks. However, incorporating QoS in WMSNs is very challenging as it requires maintenance of QoS parameters of multimedia content as well as resource constraints of WSNs. In the rest of the section, we briefly discuss the general QoS parameters of multimedia content, additional challenges in WMSNs as compared to WSNs and suitability of cross layer design to meet both the QoS guarantees and resource constraints in WMSNs.

QoS parameters in multimedia applications are well explained by Barghwa [3], who parameterizes them as accuracy, precision, and timeliness. Maintaining these three properties, in addition to energy management, is crucial to achieving QoS in WMSNs. In the context of WMSNs, maintaining accuracy means reporting the observed phenomenon without loss of fidelity. Maintaining timeliness means guaranteeing the delivery of each multimedia packet within a certain play out deadline. Maintaining precision requires the guarantee of high bandwidth availability for the smooth transmission of high data rate packets, over the network. In summary, QoS in WMSNs is the guaranteeing of multiple constraints such as high bandwidth availability, end-to-end latency, reliability of received data and error control along with energy conservation.

WMSNs are a branch of WSNs but there are prominent differences between these two networks. Energy efficiency is a dominant consideration in traditional sensor networks, whereas the goal of WMSNs is optimized delivery of multimedia content based on satisfying various QoS parameters, such as delay, error rate, prioritized delivery of multimedia content and distortion. The concentration of research in WMSNs is towards achieving fidelity of information. WMSNs differ from traditional WSNs in respect to the different factors that influence their design. Firstly, WMSNs handle heterogeneous data which can consist of scalar, audio, video, image and acoustic data, all of which have varied QoS requirements. Thus these networks incorporate service differentiation to allow differentiated processing of each application flow. Service differentiation can be provided at all layers of the protocol stack, based on different metrics, like priority of application and remaining playout deadline of a packet.

Secondly, WMSNs are very sensitive to error, because errors lead to packet drops which result in jitter and distortion in the received picture, video or audio data. In certain applications like traffic and habitat monitoring, loss of some information can be tolerated but in other applications, such as, surveillance or battlefield monitoring, error free delivery of multimedia content is crucial. Further, delay is already a constraint on these networks which make error recovery protocols that involve retransmissions unsuitable for these networks. Thirdly, multimedia data transfer requires high bandwidth, which is another factor that influences the design of WMSNs and differentiates them from traditional sensor networks. WMSNs require low complexity coding techniques that provide high compression efficiency as well as resiliency to errors. In WMSNs reliability is very closely related to the coding algorithm being used at the application layer. Thus reliable and real time transport protocols in WSNs cannot be applied to WMSNs without significant modification.

Multimedia data is delay sensitive, thus, the design of these networks is focused around reducing latency overhead at each layer and speedy delivery of each packet to the destination. This involves labeling of the playout deadline of each packet by the application layer, speedy forwarding of these packets by transport to the lower layers, delay optimized routing at network layer and delay based scheduling at MAC layer.

Wireless networks by nature have an interdependence between all layers of the protocol stack. This interdependence can be exploited, through cross-layer cooperation, to guarantee QoS constraints like latency, distortion, reliability, throughput and error rate. In traditional layered approach services and responsibilities are divided among layers and each layer works independently, with little or no communication with other layers. Cross-layer design allows communication and exchange of information across different layers to reduce processing and latency overhead and optimize performance gains. For example, the application, transport and Physical layer can cooperate to adjust source and channel coding rate, to allow energy conservation, increase in throughput and optimal utilization of resources. The network, MAC, link layer and physical layer together ensure timely delivery of each transmission, increase in throughput and decrease in level of interference and retransmissions. Due to this, cross-layer design is fast gaining popularity in wireless networks and there has been rapid research in this area in the past few years. Authors in [11] present a detailed overview of the different types of cross layer designs that can be implemented in wireless networks and their limitations and drawbacks.

Akilidz et al. [8] discusses in detail the requirements and challenges present at each layer of wireless multimedia sensor networks. While these networks are fast gaining importance and a lot of work has been proposed since the survey, there are still many issues that need to be addressed. Further the survey only briefly discusses the cross layer interaction of different layers. In [9], authors discuss multimedia communication over wireless sensor networks, with reference to application, transport and network layer independently and do not consider cross-layer solutions in WMSNs. In [10] also, authors discuss all layers except the physical layer, which holds considerable significance in achieving QoS guarantees in WMSNs, they also do not highlight the gains from a cross layer design.

There has been an avalanche of research work, since the survey [8]. However this research has been in diverse directions, made rather independently by researchers from different backgrounds, who work on different layers of the stack. There is a need to consolidate these research efforts towards a common goal, i.e. achieving QoS guarantees.

Two prominent approaches have been followed so far; layered and cross layered approach. In the layered approach most of the focus has been on application, transport and routing layer. In the cross layered approach different designs have been followed, from creating new interfaces between layers, merging adjacent layers, to creating completely new cross layer architecture, for achieving different optimization goals. In our work we look at recent work done under both these approaches. Our work differs from other surveys as follows:

– We look at issues in WMSNs from the viewpoint of achieving QoS
– We provide an outline of QoS parameters that can be satisfied at each layer

– Our focus has been to survey the more recent literature, which constitutes of several cross-layer protocols for WMSNs
– We provide an in depth discussion on adopting cross layer approach for meeting QoS guarantees in WMSNs
– We also provide a road map of tasks to be undertaken in the future

The remainder of this paper is organized as follows. In Sect. 2 we present a brief overview of the advancements made at different layers of WMSNs. Section 3, is an attempt to categorize the different efficiency gains that can be achieved through cross layer interaction in WMSNs. Section 4 contains a review of the different cross layer schemes in WMSNs and Sect. 5 provides a detailed discussion on ideal cross-layer design in WMSNs as well as future directions.

2 A Layered Approach

Wireless Multimedia Sensor Networks, are comprised of interconnected, heterogeneous sensor nodes, which interact with each other, to gather meaningful multimedia data from the environment. For example, a wireless surveillance sensor network, can consist of heterogeneous sensor nodes, like PIR sensors, audio and video sensors. Any movement detected by PIR sensor can trigger the nearby audio and video sensors to quickly gather more information about the intrusion. Similarly, a plethora of other applications are taking advantage of wireless multimedia sensor networks [4–6] to help make more informed decisions. Depending on the nature of application and the optimization goal, different research efforts focus on different layers of WMSNs, to achieve QoS guarantees.

In [5], a network of self-organizing video sensors has been deployed in a zoo to monitor the animals. This network uses a proactive routing protocol to predict when a link will be broken and establishes fresh routes even before the failure occurs. Further the scheme injects non-predictive video frames whenever a frame loss occurs to minimize the distortion that occurs at the receiver. In [6] a multi-camera network of heterogeneous nodes is proposed for detection, tracking and classification of moving objects within a certain area. Another proposal [7] aims to solve energy related problems during target tracking in WMSNs. The target motion information is extracted by a forecasting algorithm, which is utilized to awaken sensor node in the vicinity of future target position. The sensor nodes decide whether to participate in target detection based on residual energy and signal strength.

These applications have given rise to the need to offer better and more precise quality of service (QoS) for transmissions over sensor networks. While energy conservation is still one of the concerns of WMSNs, the priority of WMSNs is achieving application specific QoS. There exist various issues regarding QoS at each layer of WMSNs, designing a low complexity codec that provides high compression efficiency as well as high resiliency to errors over lossy channels is an important concern at the application layer. At the transport layer reliability, congestion control, delay minimization and error control are very significant to providing QoS guarantees. QoS based route discovery and forwarding scheme needs to be employed at network layer. The MAC layer protocols should incorporate priority based and latency aware scheduling algorithms. In the remaining of this section, the aforementioned issues are discussed at length, with respect to different layers.

2.1 Application

The heterogeneous nature of traffic and the diverse QoS constraints of each traffic type in multimedia communications, pose many challenges for WMSNs. One of those challenges is to clearly define the different QoS criteria for each traffic type and fulfill each criteria within the same framework. Coding schemes play a very important role in accurately setting the QoS parameters like maximum allowed error rate and bandwidth requirement of each traffic type. There are different video, audio and image codecs each with different properties and advantages, available for multimedia coding. Another challenge is maximizing overall compression efficiency while reducing redundancy in the network and lowering the computation overhead on the energy constrained sensor nodes. Pixel-Domain Wyner-ziv encoder is considered as the most suitable coder for sensor networks [8,9] but the latency introduced by excessive on line feedback by the decoder presents as a serious drawback.

Automatic rate selection (ARS) [12] performs pixel domain Wyner Ziv video coding with slice structure and ARS. This technique is aimed at overcoming system latency related to feedback information and rate control adaption problems. The ARS claims to improve performance over exhaustive rate selection(ERS) and quick rate selection(QRS) schemes. ARS sends feedback to the encoder only when the slice is decoded unsuccessfully. The encoder maintains an ARS table, which is built by experimental results and contains a mapping of side information quality and corresponding coding rate choices that can successfully decode side information. When the encoder receives the side information quality via feedback, it looks at the ARS table and accordingly sets a coding rate to send appropriate number of parity bits that will be decoded successfully. The encoder will continue to send at different coding rates till the decoder can successfully decode the slice.

Wang et al. [13] propose a protocol divided into two phases, first phase uses entropy based divergence measure (EDM) to measure the compression gain from joint encoding of spatially correlated cameras. This step is done before images are taken; it is based on the correlation degree of the overlapping FoVs of spatially correlated cameras. Once the performance of the joint encoding is estimated, an optimal coding clustering hierarchy is built- that maximizes global compression gain as well as provides reliability at the decoder. Maximization of compression is achieved by choosing the set of clusters with the minimum entropy while reliability is guaranteed by ensuring that each camera node is covered by at least two chosen clusters.

In [14] authors address the variable channel capacity and in-network processing challenges associated with WMSNs. This scheme also reduces query latency through a combined push-pull strategy. A mediator node which is more important than other nodes in term of coordinating the procedure of cache coherency and update messages forwarding. These nodes lie between source nodes and cache nodes and are closer to the source nodes. The communication between source node and mediator node is push based whereas communication between cache node and mediator is pull based.

There is a need to design low complexity coding schemes, which reduce encoding overhead and system latency. Further, schemes that can provide in-network multimedia processing, to reduce redundancy, are a good direction for future research.

2.2 Transport

Transport layer plays an important role in real time, delay constrained communications over sensor networks, to provide rate control, congestion detection and mitigation, end-to-end delay and reliability guarantees while also meeting energy constraints. Particularly, in WMSNs this role is enhanced, since there exist heterogeneous traffic flows, each having specific reliability, error and delay constraints. The Transport layer in WMSNs should be able to provide differentiated reliability and delay guarantees to each traffic flow. This is specially relevant to achieving timeliness and accuracy of data in WMSNs. Existing transport protocols for WSNs, are not suitable for WMSNs as they are designed to provide loose delay bounds, no service differentiation and event reliability rather than application specific reliability. Authors in [15], discuss the effect of multimedia communication over existing transport protocols on packet loss, jitter, PSNR and bandwidth utilization and conclude that existing transport protocols perform poorly for real time multimedia data.

In conventional sensor networks, reliability is either considered to be end-to-end [23,24] or event to sink [18,17]. The notion of reliability in WMSNs cannot be described in either of these two capacities as the reliability of multimedia data is measured in terms of the fidelity or quality of the phenomenon observed. The fidelity of data received at the sink can only be measured in light of application layer coding techniques. Most application coding algorithms produce frames of unequal importance, where some frames have a higher contribution to picture quality than others. In this case, reliability can be defined as the minimum percentage of high contribution frames that are required to be received correctly, in order to achieve an acceptable picture quality. Unequal error protection (UEP) strategy can be adopted to provide differentiated error protection and prioritized processing of packets of higher priority.

Another challenge at transport layer, is keeping packet loss rate below a tolerable threshold, since a high packet loss rate adversely effects reliability and picture quality. Several, traditional transport protocols, employ caching of selected packets at intermediate nodes to recover from packet loss. Pump slowly fetch quickly (PSFQ) [16] is designed to distribute data from sink to sensors by pacing data at a relatively slow-speed, but allowing nodes that experience data loss to fetch any missing segments from immediate neighbors very aggressively. RMST [24] utilizes caching at intermediate nodes and selective NACK to provide hop-by-hop or end-to-end recovery of lost packets. Similarly, multimedia distributed transport for sensor networks (DTSN) [21] is a transport protocol for real time streaming in Wireless Multimedia Sensor Networks. It proposes to guarantee reliability by recovering lost packets through caching of packets at intermediate nodes and a selective repeat mechanism. However, caching is unsuitable for real time multimedia communication for two reasons. Firstly, multimedia data has high data rates, thus caching at intermediate nodes will prove to be memory intensive in resource constrained sensor networks. Secondly, real time data has strict delay bounds, NACKs to recover lost packets will not only consume energy, lead to increase in traffic but also add to packet delay. Therefore, schemes that employ admission control to limit traffic within network capacity and prevent packet loss from occurring are more suitable for WMSNs.

Due to high data rates, congestion can easily occur in WMSNs, specially if nodes are displaced close together. Congestion leads to late arrivals and packets that arrive beyond their playout deadline are assumed to be lost in real time multimedia application, therefore, their arrival does not contribute to the quality of multimedia data. Existing approaches to detect congestion in wireless sensor networks are directly applicable in WMSNs but new algorithms to avoid and mitigate congestion while preserving quality and application constraints need to be investigated. Some, existing congestion control protocols in WSNs are mentioned below.

CODA [22] provides congestion detection on buffer length and channel sampling. Once a local node detects congestion, it broadcasts a back pressure signal to its neighbors and continues to broadcast this signal, till the source receives the message and throttles its rate. In [20], authors provide service differentiation and propose a priority based rate control protocol for congestion control in WMSNs. Queue based congestion control protocol with priority support (QCCP-PS) [19] provides congestion control through adjustment of sending rate of each traffic source based on the congestion condition and its priority index. QCCP-PS contains a congestion detection unit—which measures congestion based on queue length, a

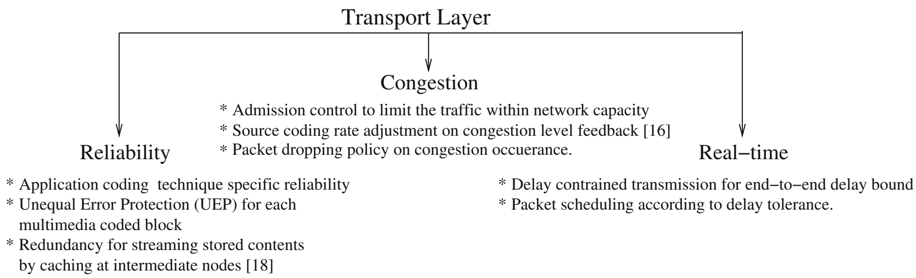

Fig. 1 Requirements of transport layer in WMSNs

rate adjustment unit (RAU)—that adjusts the rate of each child node according to congestion level and source priority index and congestion notification unit (CNU) which notifies each child node of the new rate. Thus instead of decreasing the sending rate of all traffic sources it decreases the rate of all traffic sources according to their priority. A similar, priority based packet dropping policy and rate control scheme is required for WMSNs.

Transport layer has an important role in achieving timeliness and accuracy of delivered data. Both these QoS parameters can be satisfied by providing congestion control, deadline aware scheduling of data and reliability at transport layer. The requirements of transport layer in WMSNs are given in Fig. 1. It is a huge challenge to provide congestion control and reliability in the face of high data rates and severe energy constraints. Congestion control algorithms should be able to detect congestion before it occurs and provide congestion mitigation based on priority of each traffic. Moreover, each multimedia coded frame has an unequal contribution to overall distortion, at the transport layer Unequal Error Protection (UEP) strategy can be employed to prioritize in time delivery of those frames that have a higher contribution to over all distortion. Overall real time delivery of multimedia content is critical in WMSNs, this can be enforced through delay aware transport protocols. Reliability is crucial in WMSNs and there is need for novel transport protocols, which can guarantee coding algorithm specific reliability.

2.3 Routing

One of the challenges of routing protocols in WMSNs is to identify the set of metrics that will optimize network performance as well as provide application layer specific QoS guarantees and energy conservation. These QoS metrics include end-to-end delay, packet loss, total number of hops, bandwidth, link quality and energy. Geographic routing protocols are more suitable for delay sensitive data delivery such as WMSNs, these protocols inherently choose the shortest path to the destination. Moreover, these protocols conserve energy and bandwidth during route discovery and maintenance, since discovery request is only propagated to a single hop as compared to protocols which adopt a flooding approach. Savidge et al. [29] propose a light weight geographic routing protocol which aims to achieve end-to-end delay guarantees by evaluating the position relative to the base station, the remaining energy and the queue length of the next hop nodes. Another scheme [26] uses geographic greedy routing to support hole bypassing and minimizing end-to-end transmission delay.

Considering the nature of multimedia data, which requires application specific reliability guarantees, multipath routing is also a good choice. Multipath routing can provide load balancing, reliability and higher aggregate bandwidth. However this technique may increase the complexity of the protocol as it will require appropriate schemes for fragmentation and defragmentation of packets—probably using sequence numbers—and collision avoidance at MAC layer. Further disjoint nodes need to be set up to avoid congestion on a particular path. Energy Efficient and QoS aware multipath Routing (EQSR) protocol [25] provides service differentiation to allow delay sensitive traffic to meet deadlines, end-to-end delay guarantees as well as reliability through redundancy.

Several routing protocols for WMSNs have been proposed with different objectives as well as different set of metrics. Some of these protocols are mentioned below. AntSensNet [27] is a routing protocol based on the principles of Ant Colony Optimization-based routing. It is a clustered routing protocol that builds clusters into colonies, and then finds optimal routes between cluster heads satisfying the criteria of each application. It determines routes for different traffic type on the basis of delay, packet loss, remaining energy and available memory. Whenever a cluster head has to discover an optimal route from itself to the sink, it generates Forward Ants (FANTS) to search for paths leading to the sink. These FANTS store the minimum residual energy and cumulative queue delay, packet loss and available memory of each node it has visited. Each next hop cluster head is chosen according to a certain probability, which is calculated over normalized values of remaining energy, delay, packet loss, available memory and bandwidth of each neighbor of the cluster head. The sink selects the most appropriate route after assessment of each FANT received by comparing it with the parameter values set by each application.

Multi-constrained routing algorithm (MCRA) [28] takes into consideration different service requirements of each traffic flow. It takes various service constraints including end-to-end delay, end-to-end packet loss, residual energy of each node and hop count of each path. It is based on query dissemination data delivery mode, where the sink disseminates an interest downstream and each downstream node that receives the interest checks if its residual energy, packet loss ratio and end-to-end delay are all greater than a certain threshold, if so, the intermediate node is added to the path from sink to source. When source node receives multiple interests of same query type from different routes, it chooses the path with the minimum hop count and sends data on the chosen path.

Another proposal [31] aims to provide the necessary bandwidth to the multimedia applications through non-interfering paths while increasing network lifetime. The algorithm builds a single path from source to sink but additional paths can be established incrementally, if network conditions require, e.g. if there is congestion or bandwidth shortage. The main idea of this routing protocol is that once a path is chosen, all the nodes interfering with the path are put to sleep. This allows for lesser collisions, thus lesser number of retransmissions as well as energy conservation. According to the author, the overhead of adopting an incremental approach is a trade off with increased throughput.

EDGE [32] is a greedy routing algorithm based on directed diffusion. Its objective is to maximize throughput and minimize delay. The proposal uses ETX metric to measure the link quality. To calculate the path ETX, it takes the maximum of the sum of ETX value of every consecutive three hops on a path. At the sink different paths are evaluated based on their ETX value and total delay.

S-AOMDV [33] is a multipath routing scheme for video delivery over WMSNs. This proposal is based on packet and path priority scheduling where the packets are classified according to their priorities or contribution to overall distortion and higher priority packets are transmitted through paths with better conditions. In case of unavailable bandwidth, the packets with lesser priority are compromised. The path conditions are continuously updated to provide the true picture of the network and adjust scheduling accordingly. Table 1 summarizes the metrics considered by each of the aforementioned routing protocols.

Table 1 WMSN routing protocol with link cost evaluation metrics

Proposal	Multipath	Bandwidth aggregation	Load	Packet loss	Hop count	Residual energy	End-to-end delay
REAR [29]	–	–	Yes	–	–	Yes	Yes
EDGE [32]	–	–	–	Yes	–	–	Yes
MCRA [28]	–	–	–	Yes	Yes	Yes	Yes
AntSensNet [27]	–	–	–	Yes	–	Yes	Yes
SAOMDV [33]	Yes	–	–	–	Yes	Yes	Yes
EQSR [25]	Yes	Yes	Yes	Yes	–	Yes	–
TPGF [26]	Yes	–	–	–	–	–	Yes

In continuously changing network environment, a routing protocol must provide route maintenance, however very little attention has been given to this aspect. Active routes require to be monitored continuously for changes in bandwidth availability, link error rates, energy and delay. Conventional route maintenance techniques like exchange of HELLO packets or listening to neighbor's activity [34] to predict link failure, incur a lot of overhead in WMSNs. Other ad hoc network protocols, which rely on link layer acknowledgments, also incur a lot of overhead and are not suitable for WMSNs. Some algorithms in which nodes broadcast their current status to neighboring nodes, whenever a significant change occurs on the node e.g. when energy of a node reaches a certain threshold are more appropriate. Moreover, traditional route maintenance algorithms are designed to recover from link failure, whereas, route maintenance in WMSNs needs to be performed on the ability of the path to meet application specific QoS requirements like delay, available bandwidth, error rate etc.

2.4 MAC

QoS cannot be provided without the assumption of a MAC protocol that works towards guaranteeing application level QoS requirements. MAC layer possesses special importance among all layers as it is responsible for efficient medium access, which involves reducing number of collisions and retransmissions, minimizing energy consumption, minimizing interference, maximizing concurrency and maximizing reliability. A QoS aware MAC layer is particularly important in WMSNs, since it can provide end-to-end delay guarantees, distortion minimization as well as increase in throughput by incorporating service differentiation, efficient medium access and error control. Both contention based and non-contention based MAC approaches can be used to provide QoS to heterogeneous traffic in WMSNs.

Service differentiation is the most adopted technique to provide QoS at MAC layer. In WMSNs, traffic can be differentiated in terms of traffic class, remaining time to deadline, distance traveled, resources consumed and overall contribution to distortion. Several different differentiation methods have been employed in literature. Some of the most common differentiation methods are briefly discussed below.

– *Variable contention window size, duty cycle and IFS* There exist many MAC layer schemes providing differentiated access in traditional wireless sensor networks, by varying inter frame size and contention window size [35–37]. Saxena et al. [35] propose a MAC layer protocol that is based on CSMA-CA approach and aims to provide QoS for multimedia communications over sensor networks while conserving energy. It provides differentiated service to each traffic class through dynamic adjustment of contention window (CW) size. Service differentiation is achieved by setting different CW adjust-

ing parameters for each class. Thus a low priority traffic class's CW increases faster and reduces slowly, whereas a higher priority traffic classes's CW increases slowly and reduces faster. Energy conservation is provided by adjusting the duty cycle according to the dominantly processed traffic on a node.
DiffMAC [36] is a modification of [35] and provides differentiated services to different traffic flows in WMSNs. PSIFT [37] is also a CSMA-CA based MAC protocol which prioritizes traffic classes on number of hops traversed and provides differentiation by varying contention window size and Inter frame size of each class. An innovative strategy adopted by PSIFT allows the suppression of report messages to minimize collision probability. When a node receives a certain amount of ACKS corresponding to an event, it removes that packet from its queue. This approach coupled with service differentiation ensures that packets with higher priority are transmitted earlier.
– *Multiple Queuing* Some MAC protocols also employ multiple queuing similar to 802.11e, to provide service differentiation. EQ-MAC [38] is a hybrid scheme, which uses both contention free TDMA and contention based CSMA to exploit priority scheduling of different traffic flows. It provides service differentiation through a queue management scheme, enabling higher priority traffic greater chance to acquire medium and thus reducing latency.
– *Changing contention period* Some MAC protocols incorporate additional listening periods during their sleep cycle or position their listening periods in a manner, that allows high priority data with greater opportunity to gain channel access. PQ-MAC [39] is an interesting scheme that provides service differentiation through a doubling strategy. It adds an advanced listening slot during its sleep cycle just to forward high priority data. Thus it aims to reduce latency of delay sensitive traffic, by allowing it to transmit even during sleep cycles. MAQ [40] integrates CSMA/CA and TDMA to support fair and predictable medium access for delay sensitive traffic. It provides interleaving of CFP and CP to allow low latency channel access to delay sensitive traffic. This scheme provides better performance than schemes where the CP is at the beginning of the frame and delay sensitive traffic arriving after the CP phase has to wait for the start of the next frame to con tend for channel access.

MAC layer must be given serious consideration in order to truly achieve QoS guarantees in WMSNs. Current literature on MAC layer optimizations, provide service differentiation, through dynamic duty cycles, priority based queuing and channel access, for each traffic flow. This will reduce the MAC layer delay for real time and delay sensitive traffic by providing faster access and processing to them. It is also important at MAC layer to reduce the probability of collision among neighboring nodes, as retransmission of lost packets only adds to delay overhead, which is not desirable in WMSNs. Moreover, lost packets add to jitter and distortion in WMSNs. There is also a need for error correction schemes, that do not require retransmission of information.

2.5 Physical

Wireless Sensor Networks have been implemented on different physical technologies. The most commonly used technology is IEEE 802.15.4, which works in two modes, beacon enabled and non beacon enabled. Over the years, 802.15.4 standard has emerged to be a prominent technology supporting a variety of applications. There are various studies [41,42] and experiments in literature, which measure the performance of 802.15.4 for supporting wireless sensor networks. Multimedia communications demand low latency and high data rate supporting technology. IEEE 802.15.4 can provide high data throughput in non- beacon enabled mode, but at the expense of high energy consumption. Changsu et al. [43] propose an enhancement to 802.15.4 networks to allow high data rate communications and energy conservation at the same time. The proposed scheme adaptively adjusts the active duration in the Beacon-enabled mode based on the data traffic information. This enhancement helps provide high data throughput with low latency and energy consumption. Another scheme [44] proposes the adjustment of Beacon Interval (BI) and Superframe Duration (SD) in the IEEE 802.15.4 MAC superframe accompanied with RED (Random Early Detection) queue management to improve the performance of WMSNs by reducing end-to-end delay and packet drops.

IEEE 802.11e standard provides service differentiation and QoS support for different traffic classes. It is therefore considered as a very suitable technology for WMSNs. Many layered and cross layered [35,70] schemes have exploited this standard to achieve high throughput and low end-to-end delay.

Ultra Wideband (UWB) technology is fast gaining popularity for high data rate wireless sensor networks. UWB enables short distance communication with high data rates, which makes it a perfect choice for WMSNs. Eirine et al. [45] elaborate on UWB technology's physical characteristics and propose schemes at network and MAC layer to support UWB physical layer in order to achieve maximum efficiency through this technology. Overall, this technology promises to be a good candidate for WMSNs, as UWB devices can be deployed in a heterogeneous environment without interfering or degrading performance of other radio services. Moreover, 802.15.4 can be used with UWB based sensor networks to provide greater flexibility. There is a need to take advantage of the above mentioned technologies, in a manner that allows simultaneous transmissions and minimum level of interference, so that delay constraints can be achieved.

3 A Cross-Layer Approach

Multimedia communications have a high bandwidth requirement coupled with strict delay and error constraints. Allowing these communications over lossy wireless channels introduces challenges of its own. In such an unpredictable environment, guaranteeing service differentiation, congestion control, reliability and distortion minimization is a paramount task. Traditional layered approach can only improve performance of WMSNs to a certain extent, but true optimization of these networks can only be achieved through a cross layer design. The inherent nature of wireless multihop networks and dependence of layers on information flow from above and below provides the prime opportunity to exploit the cross layer paradigm. To the best of our knowledge, none of the papers till now have clearly stated or categorized the advantages that can be gained by a cross layer design in Wireless Multimedia Sensor Networks.

The goal of a cross layer design, is to use information from different layers to jointly enhance the performance of those layers. The upward and downward information flow between the different layers, has been shown in Fig. 2. In a cross layer design, the application layer can define the QoS criteria to be followed by all lower layers. The transport layer can pass congestion and reliability information to application layer for rate adjustment and network layer for route optimization. Similarly, the network layer can make use of a variety of information like traffic QoS requirements from application layer, congestion and reliability parameter from transport layer and link and delay characteristics from MAC and physical layer for route optimization. A cross layer design can improve video quality (by

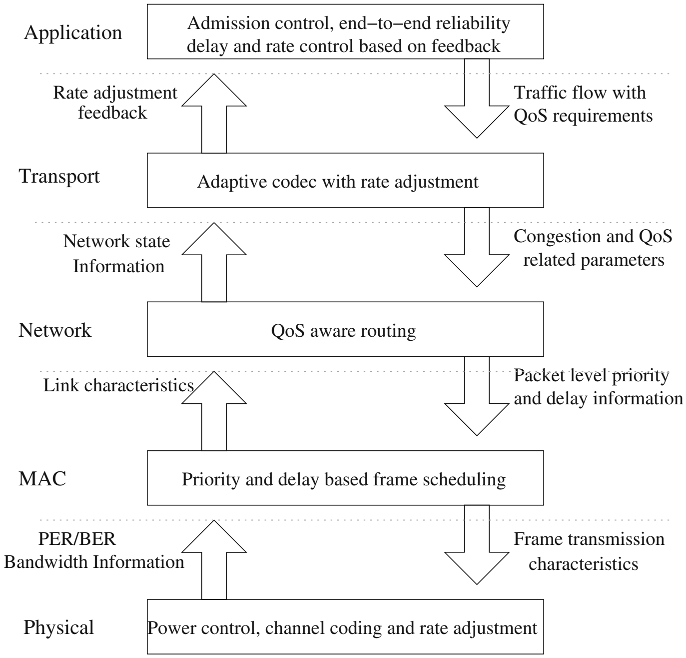

Fig. 2 Information flow in cross layer design

performing better rate control), low end-to-end delay, efficient resource management, precise admission control and network lifetime maximization. In the remaining of this section, the aforementioned benefits are explained in detail.

3.1 Video Quality

Sensor networks are resource constrained; congestion, high interference on wireless links, packet drops due to missing playout deadlines and high error rate can be very expensive.

In WMSNs, the bandwidth is shared and high data rates can frequently change underlying network conditions, which dictate the requirement for rate adaptation. End-to-end reliability, congestion and distortion rate can be used for rate adaptation. Transport layer can efficiently measure end-to-end reliability and distortion, also end-to-end delay and bandwidth utilization information from MAC layer can allow the transport layer to detect congestion and provide feedback to application layer at regular intervals.

Ad hoc transport protocol (ATP) [46] performs rate adaptation on the bottleneck congestion on a path. Congestion is estimated from bottleneck delay on a path. Each node on the path calculates the sum of its queuing delay and transmission delay and if this delay is larger than the delay of previously traversed nodes, then it is copied on the passing packet. Rate adaptation is performed by the sink, which adjusts the rate of each flow according to the most congested node on the path.

Real-Time and Reliable Transport (RT2) protocol [17] presents a real time and reliable transport protocol for WSANs. It provides congestion control as well as timely event detection and reliability with minimum energy consumption. This protocol differentiates between the reliability and delay constraints of sensor to actor and actor to actor communication. It presents the notion of delay-constrained event reliability rather than end-to-end event reliability. This criteria can be exploited for delay and loss intolerant data communication over WMSNs. This protocol provides rate adaptation, based on the difference between the observed delay constrained reliability and the desired delay constrained reliability.

ESRT [18] utilizes information at transport layer with no involvement of MAC or network layer. It performs congestion detection on buffer occupancy and provides rate adaptation on the basis of congestion notification and reliability indicator. Since ESRT bases its decision on buffer occupancy alone it cannot differentiate between packet loss due to congestion and packet loss due to wireless channel variation, it does not provide an accurate picture of network.

RCRT [52] also uses congestion as a trigger to adapt the rate. It uses a unique time to recover metric for congestion notification. If the network does not recover from congestion for two or more RTT, then the network is considered to be congested. One of the drawbacks of RCRT is that it adjusts the rate of all flows instead of just the bottleneck flow.

Minimizing distortion through reducing the load on nodes, ensuring delay constraints are met and error rate is mitigated on wireless channel requires rate adaptation through cross-layer communication between application, transport and lower layers. A source coder adjusts its information rate according to channel capacity, where in a wireless environment the channel capacity is variable and can degrade considerably. For delay constrained real-time communication, its necessary for source and channel coder to interact with each other and adjust their rates according to underlying network conditions in order to minimize distortion. In case of high error rate on a wireless channel the source coding rate may have to be decreased and channel coding rate will have to be increased. In case of congestion—indicated by transport layer—or unavailable bandwidth on a link the channel coding rate may remain the same whereas source coding rate will have to be decreased, thus a trade off between source and channel coding is required for optimal results in wireless multimedia sensor networks. In [63] source coding rate, channel coding rate and power level are simultaneously adjusted, in order to minimize distortion. It contains a centralized control unit at the network layer that determines how network resources are allocated among nodes.

3.1.1 Open Research Issues

It is a great challenge to satisfy the often conflicting requirements of wireless sensor networks and multimedia communications. Multimedia communication protocols strive to maintain a quality of image, by injecting large data rates on to the network, whereas WSNs are energy constrained networks and focus on reducing amount of data injected in the network. It is necessary to divert research efforts towards finding a balance between meeting QoS criteria of different traffic categories and energy constraints of sensor nodes.

Rate Adaptation protocols Efficient traffic rate adaption protocols need to be designed, that enable cross-layer information exchange between application, transport and lower layers, to reduce distortion by reducing load on nodes, increase throughput and reduce end-to-end latency. The goal in multimedia sensor networks is to control data rate while guaranteeing a minimum level of QoS. Delay variation and distortion provide a good mechanism for monitoring the impact of change of traffic rate on end-to-end performance. Distortion based rate adaptation schemes are more suitable for WMSNs as they adjust traffic rate according to the fidelity of the received data.

Cross-layer in-network cooperation There is a need to develop in-network processing schemes which will aim at reducing the amount of redundant and overlapping data injected onto the network. These schemes can be based on different criteria depending on the application. Priorities of data can be set previously based on traffic categorization or dynamically based on the closeness of sensor node to the event. The selection criteria needs to consider both the application layer specific metrics like overlapping FoVs and traffic priority, as well as the underlying network conditions such as, interference on link and available bandwidth.

Joint source channel coding In order to efficiently utilize the network resources with minimum energy consumption efficient cross-layer algorithms need to be designed which determine the source coding rates based on the physical layer conditions. By finding a trade-off between channel and source coding rates to avoid data loss and retransmissions, while maintaining a minimum QoS.

3.2 End-to-End Latency

End-to-end delay is a very important design parameter for delay constrained multimedia communication. Latency at all layers needs to be minimized, in order to achieve low end-to-end delay guarantees. Traditional transport layer is not aware of application specific delay requirements and all packets are treated equally in case of congestion mitigation and rate adaptation. As a result, time bound packets, waste considerable amount of time waiting to be forwarded. Passing a packets end-end delay requirement and its contribution to overall distortion can allow the transport layer to buffer and drop packets accordingly. Congestion Distortion optimized (CoDio)[47] video scheduling over wireless link optimizes a function that aims to reduce distortion as well as end-to-end delay. This protocol exploits the concept of unequal importance of different frames of a video to transmit the most important frames -within certain delay bounds -in an order that minimizes distortion.

In [48] authors propose an application layer, power-congestion-distortion [p-c-d] optimized multipath transmission scheduling algorithm. At the physical layer a suitable transmission power level is chosen that maintains an optimal SNR, thus keeping the error rate to a certain level. At the transport layer distortion caused by packet drops due to missing playout deadlines is handled. Here an accumulation based congestion control algorithm is used to predict the transmission rate, on a certain route, for a future time. Using this information from transport layer the application layer decides when and on which route should a packet be transmitted, so it can meet its delay deadlines. Thus source to sink rate adaptation can also be provided through joint transport and physical layer protocol.

In addition to an application aware transport layer, end-to-end delay can also be guaranteed at the network layer by choosing the shortest path or path with minimum delay; this delay is estimated from MAC layer which includes transmission delay, propagation delay and queuing delay. This [49] protocol incorporates the channel delay of the link including queuing delay, propagation delay and protocol processing time, available bandwidth and cost of each path to choose the least delay path. Several routing protocols, aim to achieve delay deadlines of packets by transmitting them at a certain speed. These [57,61,62] provide service differentiation as well as end-to-end delay guarantees. Authors in [61] calculate the velocity requirement according to the delay at each forwarding node and choose the most energy efficient neighbor that meets the velocity requirement. If the velocity requirement can not be met by any neighbor then the power level of the node is adjusted to meet the delay constraints. Akkaya et al. [60] provide differentiated service according to real time and non-real time traffic flows. This protocol guarantees energy efficient paths that meet end-to-end delay requirements.

Delay at MAC layer can be minimized by using a prioritized scheduling scheme which gives priority to delay intolerant applications [35]. RAP [64] is another project that considers a real-time scheduling policy for sensor networks. RAP is a communication architecture for sensor networks that proposes velocity-monotonic scheduling in order to minimize deadline miss ratios for packets. Each packet is put to a different FIFO queue based on their requested velocity, i.e. the deadline and closeness to the gateway. This ensures a prioritization at the MAC layer.

3.2.1 Open Research Issues

Delay guarantee is an important issue in multimedia networks as distortion and jitter is caused by packets arriving late at their destination and traditional layered approach adds a lot of overhead in terms of processing and queuing delay at each layer of the protocol stack. In order to provide end-to-end delay guarantees a cross-layer framework needs to be designed ,that provides prioritized congestion control and forwarding to minimize packet delay at each layer of the protocol stack.

3.3 Resource Management

The Network, MAC and Physical layer together contend for network resources.The physical layer is responsible for power and rate adaptation, information sharing can allow the physical layer to choose the most optimum transmission power that will allow increase in throughput and decrease in retransmissions. The MAC layer makes possible concurrent transmissions and link layer adjusts the rate of transmission according to the level of interference on the channel. The channel conditions shared by the physical layer can help the network layer choose the most suitable next hop node during route discovery as well as allow the MAC layer to provide better scheduling and bandwidth sharing. For example if the BER is high on a certain link then MAC layer can reduce its buffer size and routing layer will choose a route that contains nodes with low BER.

The heterogeneous nature of traffic and continuously changing network conditions in WMSNs dictate exchange of information like link capacity, interference on link, data rate , end-to-end delay on a particular path etc.

In [53] authors propose a scheme that limit multiuser interference while reducing power consumption. In [65], the author proposes a cross-layer design which provides interaction between an energy aware routing protocol,link scheduling and power control to minimize delay and transmission power. The objective of the link scheduling algorithm is to schedule as many links as possible in a time slot while maintaining an admissible transmission power scenario.

3.3.1 Open Research Issues

In WMSNs multipath routing provides gain like providing aggregated bandwidth and reliability but at the same time it increases the contention for resources, thus finding a balance between the assignment of resources for optimal utilization of good quality links is an important issue. A joint routing, scheduling and power control strategy can allow the most optimum allocation and use of resources while meeting QoS constraints and maximizing throughput.

3.4 Admission Control

Awareness of underlying network conditions at the application layer allows the WMSNs to function at their optimum capacity while preventing bottlenecks or wastage of resources. Flow admission control ensures that only traffic flows whose QoS parameters can be guaranteed by the network are admitted. Multimedia communication requires guarantees of sufficient available bandwidth, link quality and transmission speeds. Since wireless channel is shared by all the nodes, it becomes difficult to provide such guarantees without feedback from the active nodes.

CACP [66] bases its decision on the level of contention between neighbors. It calculates whether the available bandwidth is sufficient for the new flow. The proportional distribution admission control (PDAC) [50] scheme provides a network layer-based prioritized distributed admission control and bandwidth reservation algorithm that allows a mobile node to establish or discard a flow based on the traffic flow's priority and channel conditions,transmission rates and interference on link etc. In [51] an admission control scheme with multi-constrained QoS providing (ACMQ) is proposed. This scheme treats different packets differently according to their delay and reliability constraints, giving higher priority to real-time traffic.

3.4.1 Open Research Issues

In order to provide efficient admission control in WMSNs, various admission control parameters need to be taken into consideration, such as, real time information delivery, variable support for different traffic types, energy and power requirements of each traffic flow. The decision of admitting a new traffic flow, should also take into consideration its effect on congestion, reliability and fairness among existing flows.

3.5 Network Lifetime Maximization

Network Lifetime is defined as the maximum time duration till the first node dies. These multimedia nodes are battery powered and energy is a scarce resource in WMSNs, therefore, network lifetime maximization is an important issue in these networks. Most of the protocols in WMSNs have been designed with untethered delivery of multimedia content in mind, which sidelines the necessity of energy conservation and consequently network lifetime maximization. There is a need to direct efforts in this direction, by incorporating topology maintenance, congestion control, mitigating interference and limiting number of transmissions.

The above mentioned issues are not independent from each other, thus a cross-layer framework that works as a single unit as well as provides interaction and information flow between all layers of the network stack is important for optimized performance of WMSNs. In Table 2, we have provided a comparison between cross-layered and layered design, in terms of performance gains in WMSNs. The comparison takes into consideration the aforementioned design constraints, as well as service differentiation and design complexity of a cross-layered approach. Due to heterogeneous traffic flows, and differentiated requirements of each traffic, provision of service differentiation becomes crucial to achieving QoS in WMSNs. In layered approach, service differentiation is an isolated effort at a single layer, which leads to suboptimal performance. Whereas, in cross-layered approach application, network and MAC layers cooperate with each other to ensure differentiated service to each traffic flow. The drawback of cross-layered approach is that it increases design complexity. This is primarily because cross-layered approach compromises on modularity.

Table 2 Comparison of layered and cross-layer design for WMSNs

Parameter	Layered design	Cross-layered design
Traffic rate control	Achieved through end-to-end/ event -to-sink approach at transport layer (Inefficient)	Joint effort of App + transport + physical (efficient)
Delay bound content delivery	Isolated decision at either network layer or	Achieved through joint effort of network + MAC + physical (efficient)
	Mac layer	
	Physical layer	
	(Inefficient)	
Service differentiation	Partially achieved at either	Achieved through cooperation of App + Network + MAC layer (optimal solution)
	Network	
	MAC	
	(sub-optimal solution)	
Resource management	Isolated decision at either	Joint cooperation between Network + MAC + Physical (optimal solution)
	Network layer or	
	Mac layer	
	Physical layer	
	(Sub-optimal solution)	
Network lifetime	Enhanced by isolated effort at each layer	Optimally enhanced by combined effort of all layers
Complexity	Low due to modularity	Medium to High depending on number of layers involved in cross-layer design

4 Existing Cross-Layer Schemes in WMSN

Majority of existing cross-layer schemes provide cross-layer optimizations between two or three layers only. Cross-layer interaction can be between adjacent or non-adjacent layers. Some cross-layer schemes for WMSNs are discussed below.

Minimum Hop Disjoint Multipath routing algorithm with Time Slice (MHDMwTS) [54] proposes a multipath routing scheme where the source establishes a routing path with nodes that have a smallest hop count towards the sink. When a source wants to establish a path, it broadcasts a route request message. The sink selects three routes (for each source) from the multiple route request messages that it receives. The route with least delay is selected as the primary route, the second best route is the alternate route and the third best is best effort route (which is used when either the primary or alternate route fails). The sink ensures that these three routes are disjoint from each other. However, it is possible for congestion to occur at common nodes of different primary routes. Congestion is detected on common nodes by monitoring the reception queue. When the length of the reception queue reaches a threshold the source node is sent a message to shift to the alternate route. To further mitigate congestion at common nodes, the authors propose the concept of time slice, where each route is allocated a certain transmission time according to its status i.e primary, alternate or best effort. By using minimum hop count as a metric, MHDMwTS ensures end-to-end delay guarantees while preventing congestion at common nodes.

In [55] MPEG-4 video packets are sent over 802.11s. In this scheme, higher priority is assigned to forward packets (that have already traveled many hops) by placing them in higher priority queues i.e AC2 and AC1. Source packets are placed in AC2, in case the length of AC2 is below a threshold, else source packets are placed in AC0. In case the MAC buffer fills or jams, the lower priority MPEG-4 B and P frames are dropped first. This protocol reduces the end-to-end delay by providing priority based scheduling at MAC layer.

QoS MAC based on DCC-MAC [56] uses a TH-UWB physical layer and allows concurrent transmissions among different source destination pairs, by using a mechanism for interference mitigation. This mechanism is based on detecting and canceling the impact of interfering pulses that have a higher energy than the signal received from the sender. The loss by erasures can be recovered by sophisticated RCPC codes. This proposal also provides mechanisms of dynamic channel coding (DCC) and private MAC. Through DCC rates are adapted dynamically to level of interference. Private MAC allows the contention at the destination to be further mitigated by using a combination of receiver based and invitation based Time Hopping sequences (THS). Contention for a destination uses the permanent THS of the destination, but an established communication uses the THS private to a source-destination pair. Service differentiation is provided at MAC layer by employing multi-priority queuing, which helps achieve delay guarantees. The proposed scheme provides mutual exclusion with resistance to interference at the receiver, which leads to increase in throughput.

Radius and data generation Rate Adjustment (RRA) [58] describes a two phase cross-layer scheme which provides interaction of transport, network and physical layer. RRA aims to maximize data gathering while minimizing end-to-end delay. At network layer TPGF routing protocol is used to find multiple routes meeting QoS criteria. Once multiple routes are discovered, the transport layer estimates the end-to-end delay of each route and only routes meeting the end-to-end delay constraints are selected. At the physical layer the transmission radius and rate is adjusted in order to meet delay deadlines as well as maximize throughput, within a given expected network lifetime. This cross-layer scheme leads to maximum data gathering within an expected network lifetime.

This scheme [59] jointly exploits application, transport and physical layer FEC approaches to provide strong bit error correcting capability and also overcomes packet loss in multi-hop transfer. The scheme works under the framework of two- state FEC scheme based on fountain code ISCFC. RVLC scheme is used at the application layer, RSC codes are used at physical layer and redundant packets are generated at transport layer to overcome packet losses. This cross-layer scheme greatly improves the transfer reliability in contrast to other transfer schemes. It has very low computational complexity at the encoder because of which it is very suitable for WMSNs.

The distortion-minimizing rate control (DMRC) [68] algorithm minimizes video distortion by finding the optimal trade off between the video encoding rate and channel encoding rate. This scheme provides interaction between application, transport and physical layer. The scheme determines the cause of packet loss creating distortion. If the packet loss is due to congestion on the network path it reduces the source coding rate, else if the packet loss is occurring due to lossy channel, then channel coding rate is increased. To further improve the overall video quality without increasing the data rate, the concept of unequal error protection (UEP) is exploited. More important frames like I frames are protected with higher channel coding rate whereas less important B frames are protected by a comparatively less channel encoding rate. This further improves the performance of the algorithm without any additional overhead.

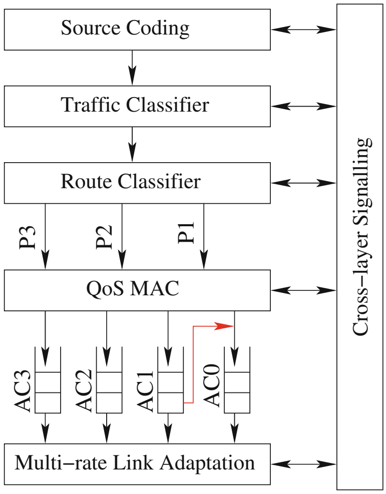

Fig. 3 cross-layer architecture proposed in [70]

In [70] authors propose interaction between application, network ,MAC and link layer to maximize number of video flows while keeping the overall distortion below a threshold. The application layer determines the end-to-end delay and coding rate; accordingly network layer employs a multipath routing algorithm to determine routes that can provide end-to-end delay and bandwidth guarantees. In case no relaying node is available (that meets the bandwidth constraint), link rate adaptation algorithm is used to switch to a higher transmission rate, if a higher transmission rate is not available then a reject message is sent to the node. In case none of the available paths can provide the available bandwidth the source increases it GoP size. At MAC layer IEEE 802.11e framework is used to provide prioritized access to the medium. The proposed cross-layer architecture is given in Fig. 3.

DS-CDMA [63] provide resource allocation in DS-CDMA video surveillance networks through joint optimization of application, link layer and physical layer. It simultaneously assigns the source coding rate, channel coding rate and power level to all nodes to reduce end-to-end distortion of the network as a whole and minimize maximum distortion amongst all nodes.

Cross-layer control unit (XLCU) [69] relies on an integrated MAC and physical layer based on Ultra Wide Band. It provides joint cooperation between application, network, MAC and physical layers. It provides admission control functionality based on hop-by-hop contracts. These hop-by-hop contracts are guaranteed through packet-level service differentiation at each hop in terms of throughput, end-to-end delay and end-to-end packet error rate. The use of UWB technology allows an integrated MAC and Physical layer which removes the need for mutual exclusion since simultaneous transmission are possible through the use of different time hopping sequences by each sender. However collisions can occur at the receiver, which is solved in the protocol by using a receiver centric scheduling algorithm. XLCU also provides dynamic channel coding to adapt to the level of interference at the receiver. XLCU covers the issue of providing end-to-end QoS guarantees and resource management but it should also involve transport layer to provide rate control.

In [71], a cross-layer scheme that provides interaction between application, MAC and physical layer is presented. The proposed scheme jointly allocates the transmission power to the source and relay nodes, the source coding rates to the source nodes, and the channel coding rates to all nodes to optimize end-to-end video quality. The authors formulate a weighted biobjective optimization problem and study the tradeoff between video quality and consumed transmission power. A similar power control and resource allocation problem is explored in [72]. The proposed scheme enables a centralized control unit (CCU) to allocate power, source-channel coding rates as well as allows the visual node to transmit at more than one available bit rate.

Cross-layer QoS routing protocol for WMSNs (CR-WMSN) [73], exploits information exchange between network and MAC layer to minimize end-to-end delay. CR-WMSN uses hop count, residual energy of node and average packet service time and channel utilization information (provided by MAC layer) to select a minimum delay path from source to sink.

QS-LEERA-MS [74] presents a cross-layer architecture for WMSNs that consists of interaction between transport, network and MAC layers. This architecture is aimed at maximizing network lifetime by distributing load over the whole network. QS-LEERA-MS consists of four components; priority based scheduler, segmentation of each stream at transport layer, load balanced routing and multi-channel based MAC. Each packet is classified as either routing packet, non-real time packet or real-time packet (where real-time packet has highest priority and routing packet has least priority) and put in corresponding multi-priority queues. At network layer a modified AODV protocol is used for path discovery. Instead of flooding the request packets like AODV, QS-LEERA-MS forwards the packet to neighbors that meet remaining energy and delay criteria set by the protocol. For the first request the shortest path is selected and then for each subsequent request the path diverges from the middle towards the outside and longer paths are determined. In case more than one path satisfies the Qos requirements then the stream is split into multiple flows equal to the number of paths and sent over multiple paths. Similarly, each path is allocated a separate channel which reduces congestion as well as contention. There are five channels where one is reserved for least priority traffic and the other four are reserved for real-time traffic.

This [75] proposes a multi-path routing protocol that assigns paths according to the priority and QoS requirements of each traffic. For example it assigns the shortest route to real-time traffic which has delay constraints and assigns path according to the energy and LQI requirements of lesser priority traffic. A priority marking algorithm is used at the application layer to mark the priority of each traffic.

Cross-layer architecture between application and transport layer is presented in [76]. A hybrid DPCM/DCT compression algorithm is employed at application layer, which is a predictive compression scheme and provides high compression efficiency with low complexity and error resiliency. This protocol aims to provide reliability by selective retransmission and congestion control. In predictive coding I and P frames are produced, where I frames have high priority since their loss leads to the loss of the whole packet. Therefore only lost I frames are retransmitted which reduces overall delay. Two thresholds are used at the buffer; stop threshold and restart threshold to provide congestion control. When a buffer on a node reaches the stop threshold it continues to receive incoming packets but sends a message to the source to stop sending packets. When the source receives this message it stops sending packets and waits till it receives a message again. When the buffer occupancy drops to restart threshold the source is sent a message to start sending again.

In [77] the problem of lifetime maximization is divided into sub-problems which includes correlation based DSC at application layer, source rate adaptation at transport layer and routing at network layer. A cross-layer protocol is described in [78], which is specifically tailored to underwater acoustic sensor network. It provides joint selection of modulation rate, FEC and transmit power at the physical layer to minimize PER. Further interference aware geographic routing scheme is defined that selects minimum delay paths from source to destination. At MAC layer a distributed hybrid CDMA/ALOHA protocol is used to provide high channel reuse and minimum retransmissions

In [79] cross-layer interaction between transport and MAC is provided for fast recovery of lost packets. DTSN transport protocol is enhanced to provide NACK based packet recovery mechanism by initiating intermediate retransmission when an out of sequence packet is detected at MAC layer.

Table 3 gives an overview of each of the cross-layer proposal discussed in this section. It provides information about the layers involved in each cross-layer design, as well as the respective functions at each layer.

5 Discussion and Future Direction

There is a growing trend towards the cross-layer approach in WMSNs. The sequential handling of packets in the layered approach incurs considerable delay and processing overhead. Since each layer is working independently, little to no sharing about the priority or QoS requirements of a packet takes place. Due to this limitation the efforts of a single layer to provide QoS guarantees do not produce optimum results. In a cross-layer approach, multiple layers work in cooperation with each other to achieve a common goal. This cooperation can exist between the application, network and MAC layer to provide real-time delay guarantees or between application, transport, MAC and physical layer to provide rate adaptation and reliability. Cross-layer information exchange between application, network, MAC and physical layer, can also be exploited, to ensure efficient resource management and energy consumption minimization. In the previous section we have discussed various cross-layer proposals, which include interaction of different layers, to achieve different QoS goals. However the ideal cross-layer framework in WMSNs must provide interaction and information exchange between all layers of the protocol stack and work as a unified framework to achieve common goals. This a paramount task as it involves protocols that enable cross-layer information exchange across different layers of the protocol stack. Although such a framework will be efficient in terms of guaranteeing QoS in WMSNs, it can lead to a very specific design that will be difficult to extend to other applications or networks. Further, the complexity of the design increases with increase in number of layers involved in cross-layer information exchange. Therefore, tradeoff between complexity and efficiency gains need to be investigated and considered for a cross-layer architecture for WMSNs.

The advantage of layered design is the ability to achieve modularity and transparency. A cross-layer design compromises on modularity, by blurring boundaries between layers, in order to efficiently support wireless services. However, in the context of WMSNs, gains from such tight integration—between layers—outweighs the benefits of modularity. In multi-hop WMSNs, marked by high data rates and unreliable wireless links, cross-layer information exchange can greatly improve performance of individual nodes thus improving the overall performance of the whole network.

An interesting direction towards designing a cross-layer framework for WMSNs, is augmenting existing layered protocols for WSNs- to make them suitable for multimedia data transfer-and allowing them to interact efficiently with each other to provide the cross-layer benefits mentioned above. This approach, rather than designing completely new protocols like XLP [67] and XLCU will provide better upgradeability as well as easy integration with existing frameworks for WSNs.

Any design for cross-layer framework, for WMSNs, needs to consider the following principles.

Table 3 Summary of existing cross-layer protocols for WMSNs

Author	Protocol	Objective	Summary	Cross-layer interactions				
				Application	Transport	Network	MAC	Physical
Yang et al. [59]	–	Maximize video quality	Cross-layer FEC	RVLC	FEC	–	–	RSC
Pompili et al. [78]	–	Maximize n/w lifetime	Interference Aware routing	–	–	Geographic routing	CDMA/ALOHA	FEC selection
		Maximize throughput	Joint selection of FEC, modulation and transmit power					Transmit power selection
			CDMA/ALOHA-based medium access					Modulation selection
Shu et al. [58]	RRA	Maximize n/w lifetime	Delay based route selection	–	Delay-constrained route selection	TPGF	–	Transmission radius and data rate selection
Zhang et al. [55]	–	Maximize video quality	Per packet priority assignment	MPEG-4	–	–	802.11s	–
			Multi priority queuing					
			Priority based packet dropping					
Jin et al. [56]	–	Optimize resource management	Interference mitigation	–	–	–	DCC-MAC	TH-UWB
			Priority based channel access using variable CW					
Pudlewski et al. [68]	DMRC	Maximize video quality	RTT triggered rate adaption	Adaptive source coding	RTT	–	–	Channel coding
Shah et al. [70]	–	Maximize admitted number of new requests	Path selection and link level rate adaptation	Distributed source coding	–	SDMR	802.11e multi-rate transmission	–

Table 3 continued

Author	Protocol	Objective	Summary	Cross-layer interactions				
				Application	Transport	Network	MAC	Physical
Melodia et al. [69]	XLCU	Optimize resource management	QoS based admission control	–	–	–	DCC	TH-IR-UWB
Bentley et al. [63]	–	Maximize video quality	Class based channel coding, source coding and power adaption	Adaptive source coding	–	–	Channel coding	Power adjustment
Paniga et al. [76]	–	Minimize Latency	Low complexity video encoder Buffer occupancy based congestion control Retransmission of lost I frames only	DPCM/DCT encoding	Congestion control	Static routing	Selective retransmission	–
Sun et al. [54]	MHDMwTS	Minimize Latency	Congestion detection and mitigation Delay based routing	–	Queue based congestion detection	Multi-path routing	–	–
You et al. [77]	–	Maximize n/w lifetime	Correlation based DSC Source rate control	Pairwise DSC scheme	Source rate adaptation	Overall link rate control	–	–

Table 3 continued

Author	Protocol	Objective	Summary	Cross-layer interactions				
				Application	Transport	Network	MAC	Physical
Tiglao et al. [79]	DTSN-CAM	Minimize delay	RNACK based packet recovery	–	Enhanced DTSN	–	Adaptive retransmission mechanism	–
Katsenou et al. [71,72]	–	Maximize video quality	Joint allocation of transmission power, source and channel coding rates	Adaptive source coding	–	–	CDMA	Adaptive channel coding
Hamid et al. [73]	CR-WMSN	Minimize delay	Route selection based on PST and channel utilization	–	–	Delay constrained routing	Modified 802.11	–
Cevik et al. [74]	QS-LEERA-MS	Maximize n/w lifetime	Traffic flow based resource reservation Traffic flow based channel allocation Priority based packet scheduling	–	Segmentation of multimedia stream	Modified AODV	Multi-channel MAC	–
Bae. et.al [75]	–	Maximize n/w lifetime	Energy, LQI, hop count and prioriy based routing	Priority marking	–	Multi-path routing	–	–

– *Service Differentiation* Heterogeneous traffic flow in WMSNs demands differentiated services for each traffic type. The framework should incorporate service differentiation at each layer to ensure each traffic's QoS requirements are adequately met.
– *Admission Control* Awareness of underlying network conditions at the time of admitting a new flow is imperative to maintaining QoS and fairness among existing flows. An admission control unit must be designed to provide admission to only those flows that (1) can be easily supported by the available bandwidth, (2) remaining energy and (3)do not congest the already existing flows. Channel sampling and congestion detection algorithms can be exploited to estimate the current load and available bandwidth on a node.
– *QoS routing* Multimedia traffic has diverse QoS requirements, thus there is a need to design routing algorithms that take into consideration several QoS metrics. These metrics include information from both upper layers as well as lower layers like delay, packet error rate, congestion, distortion, energy and even hop count. The routing protocol should be designed in a manner that it is sensitive to changes in the underlying network and can trigger early reinforcements.These reinforcements can be triggered through changes in reliability or increase in distortion at the sink or delay variation at a particular hop.
– *Rate Adaptation* Since WMSNs support high data rates on resource constrained wireless networks with limited bandwidth, a source rate adjustment unit is necessary. This unit is required to monitor the underlying network conditions and adjust source rate while guaranteeing the minimum required reliability of the application.

6 Conclusions

The survey discusses the benefits and efficiency gains of using a cross-layer approach to achieve QoS guarantees in WMSNs. Furthermore, it provides an overview of the several cross-layer proposals that exist in literature so far. This paper also provides a detailed discussion on the ideal cross-layer framework for QoS in WMSNs. We believe that this survey will further promote and facilitate research in this direction.

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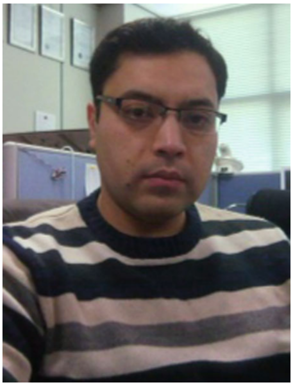
Author Biographies

Zara Hamid is currently pursuing her Ph.D. degree in Department of Computer Software Engineering, National University of Science and Technology (NUST), Pakistan. She received her B.S. and M.S. degree in Software Engineering from Hamdard University, Pakistan and NUST, Pakistan in 2004 and 2007, respectively. Her research interests include design and performance evaluation of communication protocols for wireless ad hoc and sensor networks and QoS provisioning in sensor networks.



Faisal Bashir Hussain holds a Ph.D. in Computer Engineering from Dokuz Eylul University, Izmir, Turkey (Nov 2008). After, his Ph.D. he joined the faculty of Computer Science, College of Telecommunication Engineering NUST, as Assistant Professor. Currently, he is on a Post Doc fellowship in Wireless Multimedia and Communication Systems Lab (WMCS), Chosun University, South Korea, since March 2012. His research interests are designing communication protocols for wireless ad-hoc networks, wireless sensor networks, body area networks and security issues in these networks. His research work has been published in several international journals and conferences of repute.