# A Survey on Real-time Routing Protocols for Wireless Sensor Networks

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## Abstract

**Recent advances in wireless sensor networks have led to rapid development of real-time applications. Many routing protocols have been specifically designed for these applications where real-time guarantee is an essential design issue. In this paper, the state of the art in real-time routing protocols for WSNs is surveyed, along with the highlights of the advantages and performance issues of each routing protocol and algorithm. In addition, the paper concludes with classification of recent real-time routing protocols and discusses open research issues.**

**Keywords**: Wireless sensor networks, real-time, routing protocol, survey.

## 1. Introduction

Recent advances in embedded systems and wireless communications have led to the creation of wireless sensor networks (*WSNs*), consisting of low-cost, low-power, multi-functional sensor nodes (*SNs*), that are small in size and communicate over short distances [1]. In most cases, A WSN is comprised of a large number of SNs, deployed densely and randomly in the area being monitored. In general, the SNs in a WSN sense data and convey them to one or more high power nodes called the *sink* or *base station (BS)* which do most of the complex processing. People may access them via Internet or directly with actuators which conduct actions in response. Although energy efficiency is usually the primacy concern in WSNs, the requirement of low latency communication is becoming more and more important in emerging applications. Out-of-date information will be irrelevant and even leads to negative effects to the system monitoring and control.

Real-time (*RT*) wireless sensor systems have many applications especially in intruder tracking, fire monitoring, medical care and structural health diagnosis [7]. In intruder tracking, surveillance may require the position of an intruder be reported to a command center within 15sec so that pursuing actions can be initiated in time [4]. Data in the same system may have different deadlines

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due to different requirements. For example, locations of tanks have shorter update deadlines than those of pedestrians [4]. On the fire monitoring side, applications of sensor networks are numerous. For instance, in a monitored forest area, the message of rapid temperature increasing should be transferred to the sink with timing constraints in the form of *end-to-end deadlines*. Therefore, sensor network protocols should support real-time communication by minimizing the packet *deadline miss ratio*, i.e., the percentage of packets that does not meet their end-to-end deadlines.

There are significant research results on RT communications in single-hop wired LANs (e.g., [18][19]), multi-hop wired LANs (e.g., [20]), ATM (e.g., [21][22]), and the Internet (e.g., [23][24][25]). A good survey about RT network architecture for packet-switched network is [26]. However, WSNs differ dramatically from the traditional RT systems due to its wireless nature, limited resources (power, processing and memory), low node reliability and dynamic network topology [17]. Thus, developing RT applications over WSNs should consider not only timeliness constraints, but also finding methods of energy efficient route setup and relaying of data from the sensor nodes to the sink so that the lifetime of the network could be maximized.

RT routings in sensor networks is very challenging due to several characteristics that are distinguished from contemporary communication and wireless ad-hoc networks. Very little prior work can be applied directly. First of all, a global addressing scheme is hard to build for the deployment of sheer number of sensor nodes. Second, sensor nodes are tightly constrained in terms of transmission power, on-board energy, processing capacity and storage and thus require careful resource management. Third, new designs of RT routings are necessary for offering RT QoS in WSNs with guaranteed end-to-end delivery time, delay jitter and other QoS metrics.

The rest of the paper is organized as follows. We briefly summarize the system architectures and design issues for sensor networks and their implications on RT routing in Section 2. In Section 3, we set our work apart from prior surveys on sensor networks. Then, in Section 4 current RT routing protocols are covered and discussed by the temporal sequence and we also highlight the advantages and performance issues of each routing technique and conclude with a comparative summary of the surveyed approaches. In section 5, we point out some open research issues. Finally, in Section 6 we conclude our work.

## 2. System Architecture and Design Issues

Different applications lead to different architectures and design goals/constraints. Since the performance of a RT routing protocol is closely related to the architectural model, in this section we strive to capture architectural issues and highlight their implications.

***Network Dynamics:*** Sensor nodes, sink and monitored events are three main components in sensor network. Most of the network architectures assume that sensor nodes and sink are stationary. Some of them support the mobility of sinks or a number of sensor nodes to improve the network conditions. It is more challenging to design RT routing for sending messages from or to moving nodes. In addition, the sensed event can be either dynamic or static depending on the application [27]. For instance, in a target detection/tracking application, the event is dynamic whereas forest monitoring for early fire prevention is an example of static events. So RT routing should be adaptive to the different event conditions.

***Node Deployment:*** There are two types of node deployment, *deterministic* or *self-organizing*. In deterministic situations, sensors are manually deployed and data is routed through pre-determined paths. However in self-organizing models, the sensor nodes are scattered randomly, creating an infrastructure in an ad hoc manner [2]. For example, in a disaster management scenario, a large number of sensors can be dropped by a helicopter. In both of infrastructures, the position of sink or cluster head, the node density and the scope of monitored area are crucial in RT routing design.

***Data Delivery Models:*** In applications of WSNs, the data delivery model can be continuous, event-driven, query-driven and even hybrid [27]. In the continuous delivery model, each sensor sends data periodically. In event-driven and query-driven models, the transmission of data is triggered when an event occurs or a query is generated by the sink. Hybrid models are applied in some networks using a combination of continuous, event-driven and query-driven data delivery. The RT routing protocols are highly influenced by the data delivery model, especially with regard to the minimization of energy consumption and QoS guarantees.

***Soft and Hard RT:*** Without loss of generality, QoS on RT guarantee can be categorized into two classes: hard real-time (HRT) and soft real-time (SRT) [7]. In HRT system, deterministic end-to-end delay bound should be supported. The arrival of a message after its deadline is considered as failure of the whole system. While in SRT system, probabilistic guarantee can meet requirements and some lateness is tolerable. Hence, supporting RT in WSNs means there should be either a deterministic or probabilistic end-to-end delay guarantee. It should be noted that while considering RT support in WSNs, energy efficiency should not be ignored. There is often a tradeoff between these two considerations.

# 3. Related Work

The growing interest in wireless sensor networks and the continual emergence of new architectural techniques inspired some previous efforts for surveying the characteristics, applications and communication protocols for such a research area [1][2][4][7][8].

The motivation of [1] is to give a comprehensive survey of design issues and techniques for sensor networks describing the physical constraints on sensor nodes and protocols in all layers of network stack. Some possible applications are discussed too. This survey provides a good introduction for newcomers who want to have a whole understanding in this board area. Although plenty of routing protocols for sensor networks are covered, the paper does not make a classification for them. [2] and [4] survey routing protocols for sensor networks and present classifications for the various appropriate category. Meanwhile, they highlight the advantages and performance issues of each routing technique. Since lacking a comprehensive list of recently proposed RT routing protocols, these surveys can not reflect the current state of art in real-time routing research.

[8] classifies the mechanisms that have been proposed for multimedia streaming in wireless multimedia sensor networks (WMSNs) an each layer of their protocol stack. Specifically, they consider the mechanisms operating at the network layers. [7] gives a survey of real-time QoS support in wireless sensor networks including recent real-time routing protocols. The paper does

not make a classification for real-time routing protocols and the list of discussed routing protocols could not completely give the scope of the survey.

Our survey is more focused and can serve those who want deeper insight into real-time routing issues and techniques in wireless sensor networks. It is a dedicated study of the network layer, describing and categorizing the different approaches for RT routing. In addition, we summarize different architectural design issues and conclude with open research issues for further improvement.

# 4. Real-time Routing Protocols

The main obligation of RT routing is to efficiently maintain the timeliness of data delivery by supporting transmission delay bound in network layer. To the best of our knowledge, RAP [4] is the first RT routing approaches for WSNs. Admittedly, the SPEED protocol [5] is one of the most important RT routing protocols and has been an inspiration for many other RT routing protocols [6][28][29]. We explore RT routing protocols in this section.

***RAP***: Chenyang Lu et al. [4] proposed RAP, a new real-time communication architecture for large-scale wireless sensor networks. RAP is the first detailed performance study on deadline issues in multi-hop wireless sensor networks.

The architecture of RAP is shown in Fig. 1 [4]. Sensing and control applications interact with RAP through a set of Query/Event Service APIs. A Query/Event Service layer submits the query or event registration to an area. The sensor-base communication is supported by a network stack including a transport-layer Location Addressed Protocol (LAP), a Geographic Forwarding (GF) routing protocol, a Velocity Monotonic (packet) Scheduling (VMS) layer, and a prioritized MAC. RAP assumes the routing layer is aware of physical geography. A router can determine the physical location of the destination relative to itself and forward the packet in the general direction of the destination. GF is highly scalable with regard to the number of nodes, network diameter, and the rate of change in topology [14]. The proposed protocol also supports a multiple priority scheduling of packets using a VMS, which prioritizes the packets and schedules them on the basis of their required speed of transmission.

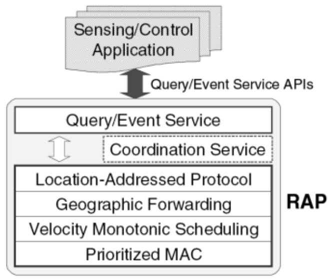


**Fig. 1 The RAP communication architecture [4].**

***Energy-Aware QoS Routing Protocol****:* Akkaya and Younis [9] present an energy-aware QoS routing protocol that could find energy-efficient path along which the end-to-end delay requirement can be met. The proposed protocol extends the routing approach in [10] and finds a least cost and delay-constrained path for real-time data considering nodes’ energy reserve, transmission energy and other communication parameters. Moreover, it maximizes the throughput for non-real-time data by adjusting the service rate for both real-time and non-real-time data at sensor nodes.

In order to provide both real-time and best effort traffic at the same time, a class-based queuing model is employed. The queuing model is depicted in Fig. 2 [2]. There is a classifier at each node to check the type of incoming packets and divert real-time and non-real-time traffic to different priority queues. The bandwidth ratio *r*, is actually an initial value set by the gateway and represents the amount of bandwidth to be dedicated both to the real-time and non-real-time traffic on a particular outgoing link in case of a congestion. Both classes can borrow bandwidth from each other when one of the two types of the traffic is non-existent or under the limits. The protocol is based on a two-step strategy incorporating both link-based costs and end-to-end constraints. First they calculate the k-least cost paths by using an extended version of Dijkstra's algorithm without considering the end-to-end delay. Second they try to find one from the candidate paths that meets the end-to-end QoS requirements and also maximizes the throughput for non-real-time traffic.

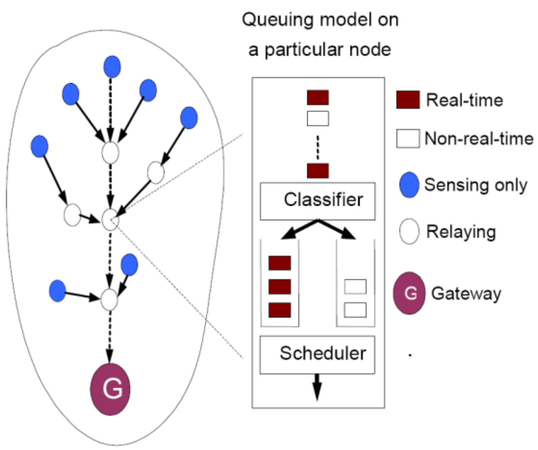


**Fig. 2 Queuing model on a particular sensor node [2].**

Simulation results show that the proposed protocol consistently performs well with respect to real-time and energy metrics. However, the proposed protocol is not scalable well in large WSNs because the routing protocol is an extended version of Dijkstra's algorithm. To support end-to-end guarantee, their approach however does not consider the delay that occurs due to channel access at the MAC. In addition, the *r*-value is set initially same for all the nodes, which does not provide adaptive bandwidth sharing for different links. Moreover, the main drawback of this approach is that it does not support multiple priorities for the real-time traffic. Then, the protocol is extended in [11] by assigning a different *r*-value for each node in order to achieve better utilization of links.

***SPEED****:* SPEED, a QoS routing protocol for sensor networks that provides soft real-time end-to-end guarantees is presented in [5]. The protocol requires each node to maintain information about its neighbors and uses geographic forwarding to find paths. In addition, SPEED strives to ensure a certain speed for each packet in the network so that each application can estimate the end-to-end delay for the packets by dividing the distance to the sink by the speed of the packet before making the admission decision. Moreover, SPEED can provide congestion avoidance when the network is congested and efficiently handles voids with minimal control overhead.

The routing module in SPEED is called Stateless Geographic Non-Deterministic forwarding (SNFG) and works with other four modules at the network layer, as shown in Fig. 3 [5]. The beacon exchange mechanism is used to collect information about nodes and their location. Delay estimation at each node is basically made by calculating the elapsed time when an ACK is received from a neighbor as the response to a transmitted data packet. By looking at the delay values, SNGF selects the nodes which meet the speed requirement. If such a node cannot be found, the *relay ratio* of the node is checked. The Neighborhood Feedback Loop (NFL) module is responsible for providing the relay ratio which is calculated by looking at the miss ratios of the neighbors of a node (the nodes which could not provide the desired speed) and is fed to the SNGF module. If the relay ratio is less than a randomly generated number between 0 and 1, the packet is dropped. And finally, the backpressure-rerouting module is used to prevent voids when a node fails to find a next hop node, and to eliminate congestion by sending messages back to the source nodes so that they will pursue new routes.

When compared to Dynamic Source Routing (DSR) [12] and Ad-hoc on-demand vector routing (AODV) [13], SPEED performs better in terms of end-to-end delay and miss ratio. Moreover, the total transmission energy is less due to the simplicity of the routing algorithm, i.e. control packet overhead is less, and to the even traffic distribution. Such load balancing is achieved through the network. One drawback of SPEED is that it does not consider any further energy metric in its routing protocol. Therefore, for more realistic understanding of SPEED's energy consumption, there is a need for comparing it to a routing protocol, which is energy-aware. In addition, the proposed protocol does not have a prioritization scheme for the packets and each forwarding node can only forward the packet at some speed less than or equal to the maximum achievable speed. However, it is not possible to forward a packet at a higher speed, even if the network can support it. To be general, due to the highly dynamic link and route characteristics the idea of per-flow reservation appears to be non-scalable in a WSN, hence SPEED might not be scalable well for large WSNs. FT-SPEED [28], as an extension of SPEED, is proposed to handle the void problem caused by high sensor failure probability in WSN. In FT-SPEED, a void announce scheme is designed to prevent the packets reaching the void through other routing path. It also introduces a void bypass scheme to route the packets around two sides of a void to guarantee the packets be delivered rather than just being dropped.

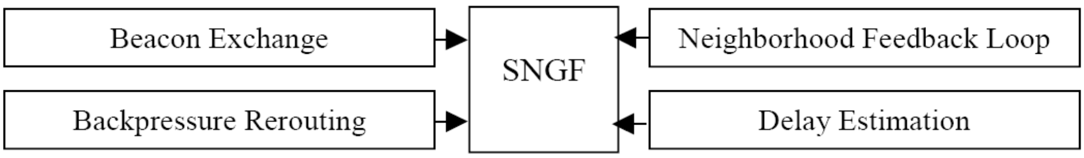


**Fig. 3 Routing components of SPEED [5].**

***MMSPEED****:* Multi-path and Multi-SPEED Routing Protocol (MMSPEED) [6] is an extension of SPEED which supports a probabilistic QoS guarantee by provisioning QoS in two domains, *timeliness* and *reliability*. QoS differentiation in timeliness is available by providing multiple network-wide packet delivery speed guarantees. The scheme employs localized geographic packet forwarding augmented with *dynamic compensation*, which compensates for local decision inaccuracies as a packet travels towards its destination. The intermediate nodes can lift speed level if they find the packet may miss the delay deadline on current speed but may be met at a higher level. MMSPEED need the support of IEEE 802.11e at the MAC layer with its inherent prioritization mechanism based on the Differentiated Inter-Frame Spacing (DIFS). Each speed level is mapped onto a MAC layer priority class. In supporting service reliability, probabilistic multi-path forwarding is used to control the number of delivery paths based on the required end-to-end reaching probability. In the scheme, each node in the network calculates the possible reliable forwarding probability value of each of its neighbors to a destination by using the packet loss rate at the MAC layer. According to the required reliable probability of a packet, each node can forward multiple copied packets to a group of selected neighbors in the forwarding neighbor set to achieve the desired level of reliability. These mechanisms for QoS provisioning are realized in a localized way without global network information, which is desirable for scalability and adaptability to large scale dynamic sensor networks. However, both SPEED and MMSPEED have a common deficiency: energy consumption metric has not been taken into account.

***RPAR****:* Real-time Power-Aware Routing protocol (RPAR) [15] is proposed to support energy-efficient real-time communication in WSNs. RPAR achieves this by dynamically adapting transmission power and routing decisions according to packet deadlines. RPAR is based on the hypothesis that there is an inherent trade-off between transmission power and communication delay. The authors also perform a set of experiments using XSM2 [16] motes to demonstrate that transmission power control may be an effective mechanism for controlling communication delays under the light workloads by improving link quality and reducing the number of transmissions needed to deliver a packet. So trade-off can be made between energy consumption and communication delay by specifying packet deadlines. Since RPAR adjusts the transmission power from time to time to meet the end-to-end delay requirement, there's no need to predefine various delivery speeds like the *SetSpeed* layers in MMSPEED. (Both SPEED and MM-SPEED use fixed transmission power.) Moreover, a novel on-demand neighborhood management mechanism is proposed to reduce energy consumption in contrast to periodic beacon exchanging scheme adopted by SPEED and MMSPEED. The neighborhood manager is invoked only when there are no eligible forwarding choices in the neighbor table for forwarding a packet. Simulations show that the forwarding policy and neighborhood management of RPAR together can introduce significantly reduction in energy consumption with desired real-time guarantee. However, the reaction time of the neighbor discovery is a potential problem to the real-time performance.

***Yuan et a*****l.**: [29] propose an energy-efficient real-time routing protocol for wireless sensor networks based on SPEED. They put forward a novel concept of *Effective Transmission (ET)* that ensures the forwarding candidates are not only nearer to the sink, but also farther from the source node with respect to its preceding node. So it can limit the area of the candidate nodes and efficiently improve the transmission. Moreover, they separate the whole path’s end-to-end delay guarantee into the sum of point-to-point *Constrained Equivalent Delay (CED)*. Each intermediate node can independently decide its next forwarding node according to the value of this link’s CED. It needs not to calculate the sum of each link’s delay on the whole path. So it can greatly reduce the overhead and simplify the route discovery process.

***Z. Khalid et al.****:* [30] propose a real-time energy-aware routing strategy for WSNs based on *Logical Network Abridgement (LNA)*. The LNA procedure is capable of describing the intrinsic state of health of the overall network. The protocol considers two cost functions: one is for time awareness and the other is for energy awareness. There are still a lot of research needed on the selection of parameter values and understanding the relationship between different parameters in the cost functions. Their future plans include extending the routing protocol to allow gateway mobility.

***DRG***: Directional Geographical Routing protocol [31] is proposed to address the problem of real-time video streaming over a WSN with constrained bandwidth and energy. DGR constructs an application-specific number of multiple disjointed paths for a *VN* (Video-sensor Node) to transmit parallel FEC-protected H.26L real-time video streams over a bandwidth-limited, unreliable networking environment.

To cater for the characteristics of video transmission, multipath routing is used in DGR to support the delivery of multiple flows instead of single-path routing scheme typically based on shortest path which be thought will drain the energy of the nodes along some path thus shorten the network life. Besides, different from traditional geographic routing scheme, DGR spreads the paths in all directions in the proximity of the source and sink nodes, which implies that packets along some paths are likely to be forwarded to a neighbor farther to the sink than the node itself. This is just for picking paths that do not interfere with each other. However, DGR relies on such assumption that the VNs take turns to send video streams to the sink, i.e., at any instance only one of the VNs is actively sending video data to the sink. This assumption is somewhat unreasonable. Thus, DGR can not be deployed in large scaled sensor networks.

***Pothuri et al.****:* [32] propose a novel heuristic solution for the delay-constrained, energy-efficient routing problem in sensor networks. The proposed hierarchical network architecture in conjunction with the proposed routing framework models the access delays caused by the MAC layer. However, they assume that each sensor node can reach the sink directly using its long-range radio. It is not practical in WSNs.

***Ergen et al.***: [33] present an energy efficient routing algorithm with hard delay guarantee for sensor networks. The algorithm is based on the model that all data packets are destined for a single sink. It aims at maximizing the lifetime of a WSN by adjusting the number of packets traversing each other. To achieve this goal, the authors first exclude the delay constraint and formulate lifetime maximization as a linear programming (LP) problem, and implement a distributed mannered solution which uses an iterative algorithm to approximate the centralized optimal one. Then, delay guarantee is incorporated into the energy efficient routing by limiting the length of routing paths from each node to the sink. Simulations reveal that the lifetime increases significantly and the delay guarantee can be satisfied. However, one may find that the result is not flexible to meet application specified delay bound generally [7].

***ACM****:* Kawai et al. [34] proposed an *Assured Corridor Mechanism* (*ACM*) based on the *synchronization-based data gathering scheme* for urgent information transmission in sensor networks, where nodes in a corridor are kept awake for fast transmission while adjoining nodes are kept silent for less collisions. The proposed approach implies that the reliability and the latency of transmission of emergency packets are improved at sacrifice of the larger transmission delay of non-urgent information and the depletion of a battery of awake nodes. They need to consider developing a mechanism with multiple corridors and multiple priorities for different emergency packets.

***Summary and classification of RT routing protocols****:* Without loss of generality, we categorize the aforementioned RT routing protocols based on *RT types*, *hierarchical architecture*, *location-based*, *scalability*, *energy efficiency* and *link reliability* as shown in Table 1. We think the classification is reasonable and can clearly display the characteristics of each RT routing protocol.

**Table 1 Classification of RT routing protocols in sensor networks**

| Routing Protocol | RT type | Hierarchical | Location based | Scalability | Energy efficiency | Link reliability |
|---|---|---|---|---|---|---|
| **RAP** | SRT | | ✓ | good | N/A | N/A |
| **Akkaya et al.** | SRT | ✓ | | low | high | moderate |
| **SPEED** | SRT | | ✓ | good | N/A | N/A |
| **MMSPEED** | SRT | | ✓ | good | N/A | high |
| **RPAR** | SRT | | | good | high | high |
| **Z. Khalid et al.** | SRT | | ✓ | moderate | high | N/A |
| **Yuan et al.** | SRT | | ✓ | good | high | N/A |
| **DGR** | SRT | | ✓ | moderate | moderate | moderate |
| **Pothuri et al.** | SRT | ✓ | ✓ | moderate | moderate | N/A |
| **Ergen et al.** | HRT | | | moderate | high | N/A |
| **ACM** | SRT | | ✓ | moderate | N/A | moderate |

# 5. Open research issues

Real-time routing is still a stimulating field of study that has raised challenges and research issues to be addressed with the proliferation of time critical applications in sensor networks. Based on our surveyed routing approaches, we conclude the following research issues and suggestions.

***RT and Energy Efficiency:*** It is a great challenge to provide RT service guarantee especially when energy efficiency needs to be put on a higher priority. How to balance energy efficiency and RT requirements is an interesting problem. A reasonable joint optimization of tunable metrics should be defined to measure the performance of designed routing protocols. There is a tradeoff between energy efficiency and end-to-end delay. For example, by a larger transmission power with high energy consumption, a message delivery velocity can be increased which can effectively decline the end-to-end delay.

***Multi-dimensional QoS guarantee:*** While offering RT QoS support, there should be a system flexibility to support different applications with respect to their different QoS requirements in the mixed traffics [7]. RT guarantee has been the main QoS requirement considered in RT-WSNs so far. However diverse RT and reliability requirements also need to be considered in QoS guarantee. In addition, meeting delay jitter constraints is another tougher problem in QoS routings [35]. Hence, a flexible integrated architecture with well defined cost functions will be very important and helpful in future development of RT routings.

***RT and Mobility:*** Most current RT routing protocols assume a WSN with low mobility. However, the targets, sensors and actuators may be highly mobile. Recent advances by adding mobile sensors in WSNs have improved the performance well, including coverage and energy efficiency. Furthermore, mobility of sensors and sinks may bring benefit to real-time guarantee. Thus, there is an interesting research area for supporting RT in highly dynamic WSNs.

***Data Aggregation****:* Data aggregation has mostly been approached as a problem isolated from the routing aspects, just considering overcoming resource constraints. However, the aggregation and routing are not independent and they may have a strong relationship. It is interesting to consider in-network data aggregation so as to allow a faster information delivery after data redundancy elimination [7]. By reducing the number of transmissions, data aggregation can help to decrease the probability of collision and congestion. Thus, the end-to-end delay can be effectively reduced. On the other hand, it brings extra delay due to the processing time for data aggregation.

***Cross-layer Design***: RT-WSNs need to guarantee both medium access delay in each single-hop and routing delay in multi-hop. In addition, different applications need specific application layer to achieve efficient performance. Recent cross-layer design can be conducted in two ways. The first aims at improving the performance of the communication protocol by taking into account parameters in other layers, while the second is to merge relevant protocols into one component. Although the latter can allow much closer interaction among protocols, it is difficult to make the relationship clear. Meanwhile, the functionality of the merged component can be complicated. Therefore, a good cross-layer design including architecture and protocols in all layers is important to the design of RT-WSNs. It will be an open research issue in the future.

***RT Support for special application scenarios:*** Rapid development in Wireless Multimedia Sensor Networks (WMSNs) and Underwater Wireless Sensor Networks (UWSNs) need special RT routing protocols to achieve real-time image/video transmission or underwater real-time data delivery. In WMSNs, multimedia data may have different priorities and the amount of data is large. Meanwhile, the design should support different QoS requirements including quality of image/video, reliability etc. On the UWSNs side, dramatically different propagation characteristics of underwater acoustic signals make the design of routing protocols more complicated than traditional WSNs. Hence, new RT routing protocols are demanded in WMSNs and UWSNs to meet special requirements.

# 6. Conclusion

Real-time routing in WSNs is an exciting area of research. The common objective is trying to provide timeliness guarantee for resource constrained wireless sensor systems. In our paper, we survey the state of the art in real-time routing protocols and algorithms for WSNs, highlight the advantages and performance issues of each routing protocol and algorithm, then classify these protocols. Finally, we pinpoint future research directions in this regard.

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