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REAL-TIME QOS SUPPORT IN WIRELESS SENSOR NETWORKS: A SURVEY

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Abstract: Real-time wireless sensor networks are becoming more and more important by the requirement of message delivery timeliness in emerging new applications. Supporting real-time QoS in sensor networks faces severe challenges due to the wireless nature, limited resource, low node reliability, distributed architecture and dynamic network topology. There are tradeoffs between different application requirements including energy efficiency and delay performance. This paper studies the state of the art of current real-time solutions including MAC protocols, routing protocols, data processing strategies and cross-layer designs. Some research challenges and future design favors are also identified and discussed.

Keywords: Real-time, wireless sensor networks, MAC, routing, cross-layer.

1. INTRODUCTION

Wireless sensor networks (WSNs) are revolutionizing the way people interact with the physical world. A large volume of sensor nodes are deployed to collect data from the environment, perform local processing, and communicate their results either with a base station (BS) which people may access via Internet or directly with actuators which conduct actions in response. Although energy efficiency is usually the primary concern in WSNs, the requirement of low latency communication is getting 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 Out-of-date information will be irrelevant and even leads to negative effects to the system monitoring and control.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) sensor systems have many applications especially in intruder tracking, medical care, fire monitoring and structural health diagnosis.

WSN differs dramatically from the traditional RT systems due to its wireless nature, limited resources (power, processing and memory), low node reliability and dynamic network topology (Stankovic *et al.*, 2003). Thus, developing real-time applications over WSN should consider not only resource constraints, but also the node and communication reliability and the globally time varying network performance. Very little prior work can be applied directly. New designs are necessary for offering RT QoS in WSNs with guaranteed end-to-end delivery time, delay jitter and other QoS metrics. This will be a new challenge for WSNs in the coming decades.

Without loss of generality, RT QoS guarantees can be categorized into two classes: hard real-time (HRT) and soft real-time (SRT). 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 system. While in SRT system, a probabilistic guarantee is required and some lateness is tolerable. Hence, supporting RT QoS 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 never be ignored. There is often a tradeoff between these two considerations.

From a layered view, the MAC should provide channel access delay (single-hop) guarantee while in network layer the routing should bound the end-to-end (multi-hop) transmission time. One may also adopt a cross-layer design to have a joint optimization. Besides, a proper in-network data aggregation strategy could be a good complement to routing protocols in reducing data redundancy and alleviating network congestion. Note that middleware is embedded to bridge the gap between applications and lower layers so as to provide abstraction and mechanisms for efficient and adaptive coordination. Some informative discussions of the design issues for WSNs can be found in (Yu *et al.*, 2004; Hadim and Mohamed, 2006). The detail will not be addressed here.

The remainder of the article is organized as follows. Section 2 aims to provide a survey on the state of the art of related MAC, routing, data processing and cross-layer designs. The challenges and potential research directions are discussed in Section 3. Finally, Section 4 contains some concluding remarks.

2. CURRENT SOLUTIONS FOR RT-WSN

In the following, some related MAC, routing, data processing and cross-layer designs are discussed respectively.

2.1 RT MAC Solutions

In WSNs, MAC plays a key role in determining the channel access delay, utilization and energy consumption. Existing MAC designs in WSNs can be classified into three categories: contention-based, contention-free and hybrid schemes. In contention-based MAC, due to the distributed and random backoff nature, it is difficult to provide a deterministic channel access guarantee. Packet collision is generally inevitable but reducible (Ye *et al.*, 2004). Nevertheless, a well-defined statistical bound is always required in offering SRT guarantee. On the other hand, contention-free MAC can be deployed with dedicated channel allocation. In TDMA-based MAC, a bounded and predictable medium access delay can be determined via time slot scheduling. However, a centralized coordinator is often required and since the traffic has to wait to transmit each time until the next round of assigned time slots, the delay incurred could not be neglected. For the completeness, the discussion of MAC here is not limited to those which can provide deterministic or probabilistic guarantee but also some commonly used MAC protocols, for example, S-MAC (Ye *et al.*, 2004), T-MAC (van Dam and Langendoen, 2003) and B-MAC (Polastre *et al.*, 2004), which reduce delay in a best effort approach.

S-MAC is a CSMA/CA based protocol. It uses periodic listening and sleeping to save energy consumption in WSNs. In order to reduce introduced latency due to the low-duty-cycle operation, adaptive listening is employed. A node overhearing its neighbor's transmission will wake up for a short time at the end of the transmission if it is a next-hop node to which the transmitter can pass data immediately. T-MAC improves the energy efficiency of S-MAC by forcing all transmitting nodes to start transmission only at the beginning of each active period. B-MAC has higher throughput and better energy efficiency than S-MAC and T-MAC. It adopts low power listening and clear channel sensing techniques to enhance channel utilization. In the classification, S-MAC, T-MAC and B-MAC only provide best effort service but not RT guarantee. To be a RT MAC, either a deterministic or statistical delay bound is required.

An implicit prioritized access protocol (I-EDF) (Caccamo *et al.*, 2002) is designed especially for HRT-WSNs. A cellular backbone network is adopted and different frequency channels are assigned. In a cell, time is divided into frames and all nodes are frame synchronized and follow earliest deadline first (EDF) schedule for packet transmission to guarantee bounded delay. A capable router node is required at the center of each cell and equipped with two transceivers for separate transmission and reception. Inter-cell communication is supported by a globally synchronized TDMA scheme and the messages are ordered by their earliest deadlines too. The mixed FDMA-TDMA scheme offers a collision-free solution. Simulations show that I-EDF can provide high throughput and low latency even in heavy loads. However, the system architecture and requirements appear impractical for WSNs. Nodes are assumed synchronized. Routers need to be deployed specifically following the cellular structure and topology knowledge is required.

Watteyne *et al.* (Watteyne *et al.*, 2006) propose a dual-mode MAC protocol which supports HRT but with more relaxed assumption than I-EDF. The goal is to guarantee deterministic transmission time compatible to application deadline. A linear network is considered with identical nodes deployed roughly along a line. Two modes are provided: protected and unprotected modes. First, unprotected mode is started. It does not employ cellular structure and collisions are possible. As soon as collision occurs, protected mode which adopts the cellular network structure with globally synchronized TDMA is used to offer collision-free transmission. Switching between two modes, the protocol is able to provide worst case delay bound and also good mean performance especially when load is low. Similar to I-EDF, the design has the following shortages: (i) energy efficiency is not considered, (ii) dedicated frequency channels are required for different cells, and (iii) a cellular network structure is needed in the protected mode. However, these mixed FDMA-TDMA schemes are promising in supporting HRT guarantees.

DMAC (Lu *et al.*, 2004) is an energy efficient and low-latency MAC designed for unidirectional data gathering tree. Conventional MAC protocols that utilize active/sleep duty cycle often suffer from significant sleep delay since in multi-hop data forwarding involved nodes are not all notified of the ongoing data delivery. By properly offsetting the active/sleep schedule of nodes based on its depth in the data gathering tree, continuous packet forwarding is maintained while nodes on the multihop path are notified of the delivery. Besides, the number of active slots scheduled in an interval is adjusted adaptively according to network traffic load to alleviate collisions. Simulations show that DMAC can achieve both energy saving and latency reduction.

DB-MAC (Bacco *et al.*, 2004) is a contention-based MAC protocol designed for delay bounded applications upon hierarchical data gathering tree. Basically, a transmission close to the source has a higher priority than a transmission close to the sink. Besides, nodes will overhear CTSs from other to facilitate early data aggregation embedded. Therefore, a node will obtain medium access with a high probability if it is close to the source. Meanwhile, it performs path aggregation as close as possible to the sources. The priority access supported enables energy saving and decreases latency as compared to IEEE 802.11 scheme.

Note that both DMAC and DB-MAC are built on application-specific data gathering tree which will limit their usage in general topology. Latency is reduced or minimized but no explicit RT guarantee is offered. Usually, a MAC protocol only addresses channel access schedule in single hop manner. It is interesting to see that DMAC and DB-MAC have MAC with some routing considerations. The result will be favorable to tree-based routing protocols and helpful to delay sensitive data gathering.

Z-MAC (Rhee *et al.*, 2005) is a hybrid MAC protocol which dynamically switches between CSMA and TDMA depending on the level of contention. It uses the knowledge of topology and a loosely synchronized clock as hints to improve MAC performance under high contention. When the hints are not obvious, it just behaves like CSMA. Generally, Z-MAC outperforms B-MAC under medium to high contention while it is a little worse under low contention. Although Z-MAC is not specifically designed for RT service, the idea of switching between TDMA and CSMA based protocols is inspiring.

PEDAMACS (Ergen and Varaiya, 2006) is a TDMA-based MAC protocol that aims to achieve both energy efficiency and delay guarantee. It considers a special class of sensor networks with high-powered access point (AP) which can reach all nodes in one hop and with nodes periodically generating packets. Topology information is gathered by AP and a scheduling algorithm is then adopted to determine when a node should transmit and receive data. PEDAMACS guarantees bounded delay and eliminates network congestion. However, the requirement of powerful AP has restricted the protocol to only few applications and weakened its attractiveness.

IEEE 802.15.4 standard specifies the physical layer (PHY) and MAC sublayer for low-data-rate low-cost wireless personal area networks (WPANs) of fixed, portable or moving devices with no battery or very limited energy consumption requirements (IEEE Std 802.15.4, 2006). It supports star as well as peer-to-peer topologies. These features make it promising for WSNs. Basically, the medium access employs CSMA-CA mechanism. However, by the optional superframe structure, time slots can be reserved for devices with time critical data upon their allocation request message. In the beacon-enabled synchronized mode, the PAN coordinator may allocate portions of the active superframe to form guaranteed time slots (GTSs) and provide contention-free period (CFP), which starts after the slotted CSMA-CA based contention access period (CAP).

For RT-WSNs, although IEEE 802.15.4 protocol has provided GTS mechanism for time critical data, details of how to use it to support explicit QoS guarantees are still developing. It is possible to let the PAN coordinator distribute GTSs corresponding to the deadline and bandwidth requirements of transmissions so as to support HRT guarantees (Francomme *et al.*, 2006). On the other hand, enhanced CSMA/CA MAC mechanisms may offer soft delay guarantees (Koubâa *et al.*, 2006). For example, priority toning strategy is used in (Kim and Choi, 2006). A node will send a tone signal to the PAN coordinator to request it alerting other nodes to defer their contentions so as to support a fast delivery of high priority frames. In (Koubâa *et al.*, 2006), traffics are categorized into high and low priority queues which employ different CSMA/CA settings. The result offers a heuristic solution to provide different QoS for messages of different priorities. Service differentiation of packets in MAC appears promising.

A comparison of the aforementioned MAC protocols is given in Table 1 to identify their QoS support and major differences.

2.2 RT Routing Solutions

Even if RT guarantee can be provided in MAC layer, packet deadline still cannot be met if there is no transmission delay bound in network layer. As mentioned before, DMAC and DB-MAC are designed on a tree topology which is a multi-hop network with packet routing capability, therefore they can naturally support a bounded delay in both MAC and network layer. For RT-WSNs, routing protocols that can provide deterministic or probabilistic delay guarantee are favored. For example, if the routing protocol is location-aware

Table 1. A comparison of the discussed MAC protocols

Name	MAC type	RT type	Topology dependent	Energy efficiency	Scalability
S-MAC, T-MAC, B-MAC	CSMA/CA	best effort	no	high	good
I-EDF	FDMA-TDMA	HRT	cell structure	N/A	moderate
Dual-mode MAC	FDMA-TDMA	HRT	cell structure	N/A	moderate
DMAC	slotted contention-based	best effort	tree structure	moderate	good
DB-MAC	contention-based	best effort	tree structure	high	good
Z-MAC	CSMA-TDMA	best effort	no	high	moderate
PEDAMACS	TDMA	HRT	no	high	low
IEEE 802.15.4	slotted CSMA/CA, GTS	best effort/HRT	no	moderate	good

or tree-based, it is easier to estimate the delay by computing the distance between the source and sink or by checking the depth in the tree. However, if a routing protocol is based on random broadcasting, it will be difficult to guarantee a delay bound. Some protocols are designed to reduce transmission or queueing delay but without deterministic or probabilistic guarantee. Therefore, in nature they do not support RT QoS but just provide best effort service.

SPEED (He *et al.*, 2003) is a RT routing protocol for soft end-to-end deadline guarantee by maintaining a desired delivery speed across the network. The core module is the stateless non-deterministic geographic forwarding (SNGF), which sends packets to the downstream node capable of maintaining the desired delivery speed. If there is no neighbor node which can support the desired speed, it probabilistically drops packets to regulate the workload. At the same time, a backpressure packet re-routing around large-delay links is used to reduce or divert the traffic injected to a congested area. The desired network wide speed is maintained such that SRT end-to-end delivery is obtained with a theoretical delay bound. Besides, the mechanism works in a localized way which makes it quite scalable.

MMSPEED (Felemban *et al.*, 2006) is an extension of SPEED which supports service differentiation and probabilistic QoS guarantee. For delivery timeliness, multiple network-wide packet delivery speed options are provided for different traffic types according to their end-to-end deadlines. In supporting service reliability, probabilistic multipath forwarding is used to control the number of delivery paths based on the required end-to-end reaching probability. These methods are implemented in a localized way with dynamic compensation for the inaccuracies of local decisions. Like SPEED, since all mechanisms in MMSPEED work locally without global network state information and end-to-end path setup, it is scalable and adaptive to network dynamics. However, both SPEED and MMSPEED have a common deficiency: energy consumption metric has not been taken into account.

A real-time power-aware routing (RPAR) protocol (Chipara *et al.*, 2006) is proposed to achieve application specified communication delay at low energy cost by dynamically adjusting transmission power and routing decisions. It allows the application to control the tradeoff between energy consumption and communication delay by specifying packet deadlines. Important practical issues like lossy links, memory and bandwidth constraints, and scalability are considered. Since RPAR adjusts the transmission power from time to time, the network topology may change frequently. Thus it employs a novel neighborhood management mechanism which is more efficient than the periodic beacon scheme adopted by SPEED and MMSPEED.

Akkaya *et al.* (Akkaya and Younis, 2003) propose an energy-aware QoS routing protocol that will find energy-efficient path along which the end-to-end delay requirement can be met. It is assumed each node has a classifier to check the type of incoming packets and divert RT and non-RT traffic to different priority queues. The delay requirement is converted into bandwidth requirement. To support end-to-end guarantee, their approach however does not take into account the delay that occurs due to channel access at the MAC. Moreover, the use of class-based priority queuing mechanism is too complicated and costly for resource limited sensors.

Pothuri *et al.* (Pothuri *et al.*, 2006) design a heuristic solution to find energy-efficient path for delay-constrained data in WSNs. They employ topology control and have a modeling of the contention delay caused by MAC layer. A set of paths between source and sink nodes are identified and indexed in the increasing order of their energy consumption. End-to-end delay is estimated along each of the ordered paths and the one with the lowest index that satisfies the delay constraint is selected. However, their solution is based on the assumption that nodes are equipped with two radios: a low-power radio for short-range and a high-power radio for long-range communication such that each node can reach the sink directly using its long-range radio. This requirement is energy inefficient and may not be practical.

Ergen *et al.* (Ergen and Varaiya, to be published) presents an energy efficient routing method with delay guarantee for sensor networks. They first exclude the delay constraint and formulate the lifetime maximization as a linear programming (LP) problem with the goal of determining optimal routing paths and maximizing the minimum lifetime of each node in the network. The LP solution is first implemented in a centralized way and then approximated by an iterative algorithm based on least cost path routing. Then, delay guarantee is included in the energy efficient routing by limiting the length of routing path from each node to the sink. The simulation shows that the maximum delay can be limited to a certain level. However, one may find that the result is not flexible to meet application specified delay bound generally.

A comparative summary of the previously mentioned RT routing protocols is given in Table 2.

Table 2. A comparison of the discussed routing protocols

Name	RT type	Link reliability	Energy efficiency	Scalability
SPEED	SRT	N/A	N/A	good
MMSPEED	SRT	high	N/A	good
RARP	SRT	high	high	good
EA-QoS	SRT	moderate	high	low
Pothuri	SRT	N/A	moderate	moderate
Ergen	HRT	N/A	high	moderate

2.3 RT Data Processing

Data processing strategies at sensor nodes can help to enhance the capability of QoS guarantee in WSNs. In-network data aggregation is able to improve energy efficiency and has an important role on the quality of surveillance, data timeliness and system overheads.

Hu *et al.* (Hu *et al.*, 2006) investigate the energy efficiency of data aggregation tree in WSNs. An analytic model based on IEEE 802.15.4 CSMA/CA is developed to compute a node's worst case delay in aggregating data from all child nodes. A heuristic algorithm is then proposed for constructing data aggregation tree to minimize total energy cost under latency bound. However, the proposed algorithm is centralized.

Zhu *et al.* (Zhu *et al.*, 2006) study an QoS-based data aggregation and processing approach for sensor networks. End-to-end latency is taken into account to determine whether, when and where to perform the aggregation in a distributed fashion. A localized adaptive data collection algorithm performed at the source node is thus developed to balance the design tradeoffs between delay, measurement accuracy and buffer overflow. Note that the design is only evaluated in a fixed network. Its operations and performance in dynamic systems need to be verified and further investigated.

Yu *et al.* (Yu *et al.*, 2006) study the energy-latency tradeoff in data gathering of mission critical RT applications. They consider packet scheduling in a tree structure and employ a precisely defined non-monotonic energy cost model. The core is to find a packet transmission schedule which can minimize the energy cost within the allowed latency. Energy saving is observed. This has also reflected the importance of an explicit energy consumption model in the system design and optimization.

He *et al.* (He *et al.*, 2006*b*) defines a four-tier data aggregation architecture with raw data aggregation, in-node aggregation, group aggregation and base aggregation for a RT tracking system called VigilNet. The architecture has been implemented in a real application. Besides, the scheme has cross-layer design. We will discuss in next section in detail. It can flexibly achieve a balance between energy, timeliness and data availability.

2.4 Cross-layer Solutions

From a holistic point of view, it is reasonable to consider RT issues cross different layers in the communication stack. The following designs have provided RT guarantee in a cooperative cross-layer architecture.

RAP (Lu *et al.*, 2002) is a cross-layer RT communication architecture for large-scale sensor networks. It is supported by a scalable and efficient protocol stack, which integrates a transport-layer location-addressed protocol (LAP), a geographic routing protocol, velocity monotonic scheduling (VMS) policy and a contention-based MAC with packet prioritization. The cornerstone of RAP is the VMS policy, which is based on packet requested velocity that reflects both distance and timing constraints. VMS reduces end-to-end deadline miss ratio by giving higher priority to packets with higher requested velocities.

MERLIN (Ruzzelli *et al.*, 2006) is a lightweight protocol that integrates routing and MAC protocols together to support energy efficiency and low latency in WSNs. Its MAC follows a hybrid TDMA/CSMA approach in which slot contention needs to be conducted at the beginning of each slot. For routing, the network is divided into time zones defined by the number of hops in a schedule table, by which nodes forward messages to the gateway over multiple hops. The localization procedure is based on triangulation and distance between pairs of nodes. The result shows MERLIN outperforms an integration of S-MAC and ESR

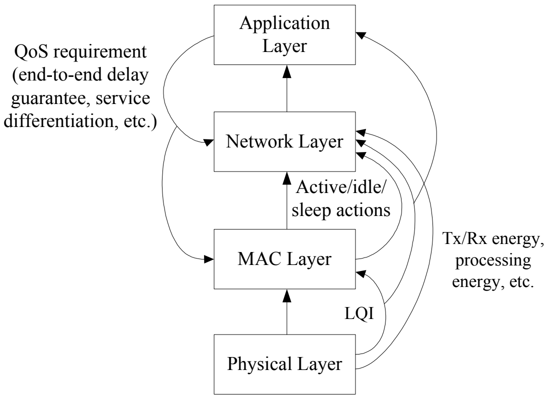

Fig. 1. Cross-layer design for RT-WSNs

(Eyes Source Routing) (Wu *et al.*, 2004) in both energy efficiency and latency. However, it should be noted that S-MAC and ESR are not designed for RT application. The delay performance of MERLIN should be investigated more specifically.

VigilNet (He *et al.*, 2006*a*) is a large scale RT sensor system for target tracking, detection and classification and aims at both timeliness and energy efficiencies. Its network infrastructure is a multipath diffusion tree rooted at bases. B-MAC is the default MAC protocol. Deadline partition method is used to guarantee an end-to-end tracking deadline by satisfying a set of sub-deadlines. Multidimensional tradeoffs between RT performance and other system properties are investigated.

Figure 1 illustrates a simplified cross-layer framework for RT-WSNs. Following the typical communication stack, parameters in lower layer are reported to adjacent higher layer. As shown in Figure 1, the cross-layer design enables a higher layer to coordinate the behavior of lower layers. Parameters of distant layers can have interactions as well. For example, the application layer may have QoS requirement like end-to-end delay bound and service differentiation, which will place a delay constraint and have priority scheduling in routing layer and MAC layer. Physical layer determines the amount of energy spent in transmission and circuit. It also provides the link quality indication (LQI) to the MAC, routing and application layers. LQI can provide a reference for the scheduling at MAC layer, reflect the reliability and robustness of routing path, and also affect the source coding at the application layer. Besides, the active/idle/sleep action at MAC layer will help optimizing the performance of routing layer. There are impacts on one another.

Generally speaking, 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 very complex. Therefore, it is better to leave some transparency between layers.

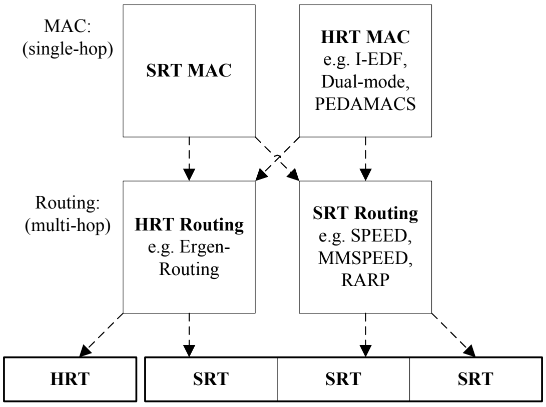

Fig. 2. Combinations of MAC and routing protocols for RT QoS support in WSNs

3. CHALLENGES AND OPEN ISSUES

To ensure the acquisition of timely information from source to destination, delay control is always at the core of a RT-WSN. Based on the survey, we have the following summary and suggestions.

3.1 Soft and Hard RT

As shown in Figure 2, for RT communication, any node participating in the WSN should be able to support both guaranteed medium access delay in each single-hop and routing delay in multi-hop. Logically, only the combination of HRT MAC and HRT routing can lead to a HRT end-to-end deadline guarantee. For example, in MAC, a contention-free protocol such as I-EDF is inherently suitable for HRT service. However, the protocol scalability, system requirements and overheads should be considered. Alternatively, the other three combinations will commonly reach SRT support. Contention-based protocols have the capability of providing statistical performance bound and packet prioritization can be embedded for enhancement. In general, people could integrate different protocols in respective layers to meet their RT requirements. It should be noted that due to the wireless link unreliability, a design with both HRT MAC and HRT routing could still fall into a probabilistic QoS guarantee.

Generally speaking, although providing deterministic delay guarantee is often more favorable for a RT system, it could easily result in an overly conservative end-to-end bound and low resource utilization efficiency especially for a large scale and dynamic WSN. Probabilistic guarantee is another option which has less system requirements and seems to be more promising. However, explicit probabilistic guarantees should be provided for SRT support. A best-effort service is insufficient.

3.2 RT and Energy Efficiency

Since sensors are usually energy constrained devices, providing RT service guarantee is challenging especially when energy efficiency needs to be put on a higher priority. This reduces the flexibility in the protocol design and gives more constraints to an optimization for RT requirements. Without loss of generality, how to make a balance between energy efficiency and delay guarantee is an interesting problem. A joint optimization of tunable metrics with well-defined cost functions may offer an effective solution. It is reasonable that a RT-WSN design may sacrifice some energy efficiency in order to achieve message delivery timeliness. For example, by a larger transmission power, a message delivery to the destination can be conducted in a smaller number of hops.

3.3 Multi-source Multi-sink Model

Most of the existing WSN protocol designs aim at multiple source to single destination model. It should be noted that the result may not be applicable to a more sophisticated multi-source multi-sink system. Conflicts can occur among cross tasks in the network. It is challenging to satisfy the deadline requirements of multiple tasks simultaneously. In wireless sensor-actuator networks (WSANs), sensors have multiple potential destinations (e.g. actuators) in event reporting (Ngai *et al.*, 2006). Besides, actuators could be mobile in conducting actions. The resulting heterogenous system is quite different from a traditional data collection WSN model with single static sink.

Note that, in WSANs, actuators are often assumed resource-rich and with high energy and communication capability. This implies a possibility of using them as fast relays to transmit data collected from sensors to a destination directly or in a few hops for time-critical service. Interesting applications are expected.

3.4 Data Aggregation

Comparing data centric with application oriented WSNs, one can find that the former usually only aims to deliver packets to destination before deadlines. In an application oriented WSN, events instead are required to be reported in time. Simple end-to-end data delay bound is insufficient (Stankovic *et al.*, 2003) for application oriented WSNs. It is interesting to consider in-network data aggregation so as to allow a faster information delivery after data redundancy elimination. This not only saves transmission energy but also helps to prevent network congestion. Application-level delay can thus be reduced. However, this may also lead to extra delivery delay due to the processing time for aggregation.

3.5 Multi-dimensional QoS Support

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. Generally speaking, they include RT reliable service, best-effort service, bursty event reporting and simple rate-matched service. A flexible integrated architecture with configurable performance metrics in well defined cost functions will be of great help to the future development of RT-WSNs.

3.6 QoS Support for Mobile WSNs

Most of the current communication protocols supporting RT QoS assume a WSN with low mobility. However, the targets, sensors and actuators may be highly mobile. A static or periodically updated neighborhood information will be insufficient. There is a need for new protocols specifically designed for supporting QoS in highly dynamic WSNs and provide effective control (He *et al.*, 2007).

4. CONCLUDING REMARKS

Supporting RT QoS in WSNs is a new area of research. A comprehensive survey of current RT-WSN solutions has been presented with respect to different MAC, routing, data aggregation and cross-layer designs. They have the common objective of trying to provide timeliness guarantee for delay constrained wireless sensor systems. Their advantages and disadvantages are discussed and compared. Besides, the design tradeoff between energy and delay is also highlighted. Although many designs may have nice energy efficiency and delay performance, for explicit RT support there are still various challenges and issues that need to be addressed. We have pointed them out for future research and potential advancement.

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