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QoS Challenges in Wireless Sensor Networked Robotics

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Abstract Wireless sensor networks and mobile robotics are two hot research topics. Integrating them leads to a wide range of new applications in many different environments such as terrestrial, underwater, underground and aerial. Where sensor networks are mainly used for large-scale monitoring and control, mobile robotics are used for performing fine-scale actions and automation. Network heterogeneity together with stringent Quality of Service (QoS) demands from applications such as voice and video make QoS support very challenging. Therefore, this paper investigates the QoS challenges in wireless sensor networked robotics and presents a novel QoS framework as solution to cope with these challenges.

Keywords Quality of Service · Robotics · Wireless Sensor Networks

1 Introduction

Wireless sensor networks are networks that contain a huge amount of small and cheap sensor nodes that are communicating through a low-power radio interface. They are typically used for large-scale sensing tasks and they are relaying the sensed information to a central base station, where the collected information is analyzed [1].

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Sensor networks are more and more integrated in daily life to monitor and control the environment in a ubiquitous and pervasive way. Applications include health care, military, industry and building automation. Although sensor networks have many advantages, there are also some drawbacks. They have resource constraints on energy, memory, processing, communication range and bandwidth. The deployment is not always straightforward and nodes can fail.

A solution to overcome or minimize these drawbacks is adding mobile robots to these sensor networks. Mobile robots are autonomous devices which are often equipped with various sensing and communication capabilities. They can act as high-performance sensor nodes and allow high-bandwidth communication. These robots can be used for fine-scale monitoring, for performing sensor node manipulations and for taking actions based on sensed information. For instance, they can deploy new nodes, detect and replace or recharge damaged or depleted sensor nodes, and they can help to alleviate the task of sensor nodes when calculations have to be performed or when high-bandwidth data has to be transported. Another advantage of adding robots is that they can replace human presence in hard to reach or dangerous environments and that they can perform monotonous and tiresome tasks [2].

Wireless sensor networked robotics enfold a wide range of new applications in complex environments. Applications are ranging from critical or non-critical monitoring applications to voice and video applications in diverse environments. All these applications have one or more (direct) Quality of Service (QoS) constraints in terms of delay, packet loss and throughput. Providing the requested QoS level in wireless sensor networks is already a challenging task [3] and this is even more true for wireless sensor networked robotics. On one hand, there is a negative impact because links can become unpredictable due to mobility and because path planning difficulties can increase the end-to-end delay, but on the other hand, mobile robotic nodes can improve the QoS because they have more capabilities and they can offer a high-bandwidth routing path to static sensor nodes.

The remainder of this paper is organized as follows. In Section 2, we give an overview of the domains in which wireless sensor networked robotics are already deployed. Furthermore, the integration of wireless sensor networks and robotics is explained in more detail and the advantages both for sensor networks and for robotics are discussed. Afterwards, in Section 3, we discuss the most important QoS metrics together with the specific QoS research challenges that arise by combining wireless sensor networks and robotics. In Section 4, we present our flexible QoS Framework as solution for the previously identified QoS challenges. Finally, Section 5 concludes this paper.

2 Wireless Sensor Networked Robotics

2.1 Integrating wireless sensor networks and robotics

Wireless sensor networks have the big advantage that they can be easily deployed compared to wired networks. Sensor nodes are small, cheap and can be used anywhere, going from enlisted monuments to hard to reach areas. Mobile robotics can be considered as high-performance sensor nodes, and as such, extending sensor networks with mobile robotics may be beneficial both for sensor networks and for mobile robotics. The general cost of deployment, movement, communication and energy is reduced and the resulting network is in general more robust and efficient.

Advantages for sensor networks Robots can perform advanced sensing tasks and calculations, they can be used for transporting high-bandwidth data and for transporting data back to the sink on behalf of the sensor network. This relieves the sensor network, and energy that otherwise would be used to forward data or perform calculations can now be used for essential tasks which prolongs the lifetime of the network.

Furthermore, robots can assist with various sensor node manipulations such as the initial deployment, moving sensor nodes on the fly, adding or removing nodes, replacing the nodes or repairing the connectivity when they are depleted or destroyed and help to localize them. They can also act as data mulers to relay information between disconnected sensor clusters and thus extending the overall lifetime of the sensor network.

Finally, robots can perform fine-scale monitoring, inspection and actions. Where the sensor network is used for large-scale monitoring and detection, the robots can zoom to a certain area or they can perform more accurate data sensing.

Advantages for robotic networks Not only sensor networks can benefit from robots, integrating wireless sensor networks and robots has advantages for the robotics too.

A first advantage is that a wireless sensor network can be considered as an extension of the sensorial capabilities of robots. These sensor networks give faster, cheaper and wide-range (environmental) information beyond the perceptual horizon of robots. This information can be used by the robots for calculations, processing and taking the right actions.

Although it is more strenuous for the sensor network, it can be used to relay the data captured by robots. This way, robots can stay in the interested region without going back to their base station.

Finally, sensor networks can be used for the navigation and localization of robots, which is very useful in places where GPS signals are unavailable.

2.2 Use Cases

Wireless sensor networks and robots can be integrated in many domains, going from traditional monitoring applications to more challenging health care scenarios. Fig. 1 gives an overview of the domains where sensor networks and robots are successfully integrated. They are discussed below in more detail.

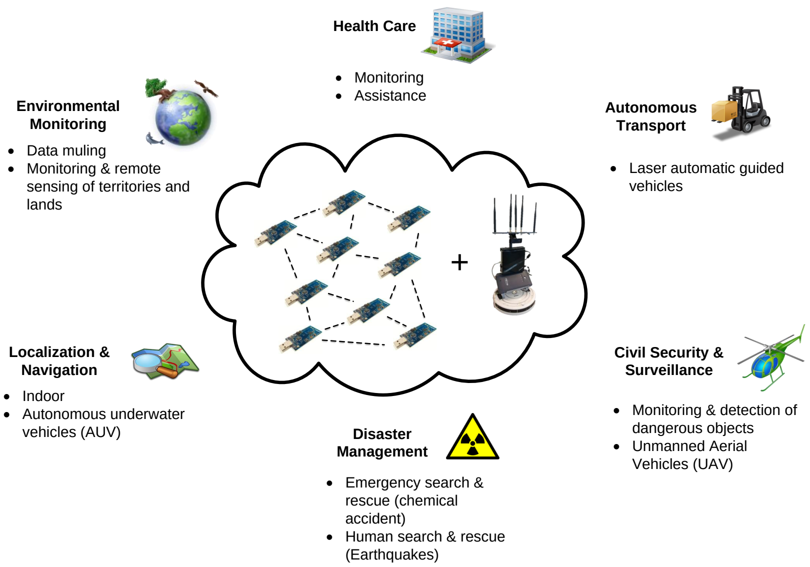

Fig. 1 Wireless Sensor Networked Robotics: use cases

2.2.1 Environmental monitoring

In [4], a robotic sensor network is used for underwater data muling. The autonomous underwater robots/vehicles (AUV) (Starbug) can locate the underwater static nodes (Aquaflecks) using vision, and they hover above the static nodes for data upload. Acoustic communication is used for broadcast and event signaling and optical communication is used for high-rate local data transfer. Another example of data muling can be found in [5], in which data mules visit locations within the communication distance of each of the static motes, download their measurements and return to a remote base station to offload the collected data.

The authors of [6] have developed a robotic sensor network for outdoor surveillance and monitoring of human living and working environments. In this case, robots are used to replace human presence in everyday working dirty, health-destructing, tiresome and monotonous jobs.

2.2.2 Health care

In [7], a robotic sensor network is used for detecting and understanding abnormal health behaviors (for instance tumbling of elderly people). The robots are used for providing help. Other applications could include remote telepresence where ill children can interact by a robot with their schoolmates and teachers.

2.2.3 Autonomous transport

An example of integrating wireless sensor networks and robotics in the autonomous transport sector can be found in [8]. The sensor network is used to improve the intelligence and efficiency of (laser) automatic guided vehicles (AGV). This approach allows inter-vehicle communication (position, speed, direction, load etc.) and distributed control which leads to a higher degree of autonomy and flexibility.

2.2.4 Localization and Navigation

In [9], an environment map free navigation algorithm is proposed in order to use wireless sensor network information for indoor mobile robot navigation. Paper [10] describes a system in which an underwater sensor network provides the opportunity to reuse the sensor network infrastructure for long baseline localization of the autonomous underwater vehicles (AUV). Such systems becomes essential for navigation and geo-referencing data gathered during sensing tasks since GPS signals are not available underwater.

2.2.5 Disaster management

Another application area of wireless sensor networked robotics is disaster management. In [11], a chemical accident emergency search and rescue system was developed. It is used for monitoring the leakage of hazardous chemicals and guaranteeing the safety of people in such areas. The robots can be used as high-performance sensor nodes (various sensors, more communication capabilities, etc.). Furthermore, the robots can manipulate the sensor nodes (replacing, changing the topology, etc.). In [12], the integration of robots and a wireless sensor network is used for autonomous navigation into rubbles and to search for living human body heat using the thermal sensor. The wireless sensor network is used for tracking the location of the robot by analyzing the signal strength.

2.2.6 Civil security and Surveillance

[13] combines wireless sensor networks and unmanned aerial vehicles (UAV) in isolated areas where communication between ground nodes might be difficult (for instance when coverage over large areas is necessary). The UAVs are then used to upload information sensed by sensor nodes on the ground or to deploy

nodes. Where the UAVs can sense over a large area at high altitude, sensor networks can monitor over very small areas. In [14], robots and wireless sensor networks are combined for autonomous navigation in an indoor area with unknown obstacles. The robots are able to avoid these obstacles and move around the region. The underlying sensor network is used for data relaying and navigation, while the robots are used for more accurate and closer monitoring when needed (for instance for detecting explosives).

3 QoS Metrics and Research Challenges

Prior to explain the QoS research challenges in wireless sensor networked robotics, an overview of the considered QoS metrics is given.

3.1 QoS Metrics

Delay End-to-end delay is the time it takes to transmit a packet from source to destination. This time includes queuing delays, propagation delays (related to the distance and medium between the nodes), transmission delays (caused to the data rate of the communication link) and processing delays. Most wireless sensor networked robotic applications will have some delay constraints. For real-time applications, these delay constraints can be very stringent.

Packet Loss Rate The packet loss rate is the amount of packets that may be lost during transmission in order to still fit within the reliability requirements. Factors that can cause packet loss are congestion, broken communication links due to node failures or mobile nodes, and bit errors due to noise, interference, distortion or bit synchronization.

Packet Delay Variation Packet delay variation is the difference in end-to-end delay between selected packets in a flow, ignoring any lost packets. This QoS metric becomes important for interactive real-time applications, such as voice.

Throughput Throughput is defined as the average rate of successful delivered data from source to destination. The difference with bandwidth is that bandwidth defines the amount of data that physically can be transmitted through the medium, while throughput is the actual data that successfully reaches the end destination. Throughput hence also takes into account packet loss and delay.

3.2 QoS Research Challenges

3.2.1 Dynamic Network Topology

Where traditional wireless sensor networks mainly contain static sensor nodes, sensor networked robotics also contain mobile robotic nodes. QoS challenges in static sensor networks are often caused by unreliable links due to fading, environmentally related link challenges (underwater/underground) and node fall out due to damage, battery depletion or displacement by nature (wind, explosion, ...). Unpredictable links due to mobility are an additional challenge in mobile robotic sensor networks. Furthermore, compared to static sensor networks, robotic sensor networks operate in more extreme environmental conditions such as earthquakes, chemical disaster environments and flooding.

3.2.2 Heterogeneous nodes

Sensor nodes are tiny low-cost and low-power devices with limited resources on processing, energy, communication range, bandwidth and memory. For instance, the Tmote Sky sensor node has a CC2420 radio with a theoretical bit rate of 250 kbps and an 8 MHz MSP430 microcontroller with only 10k RAM and 48k Flash memory. As a consequence, both the amount and the range of exchanged information is very limited and can be different for each kind of sensor node. Moreover, since energy is a scarce resource and sensor networks are often deployed in hard to reach environments that are complicating frequent battery replacements, energy saving mechanisms are applied to extend the lifetime of the network. However, this may have a negative impact on the delivered QoS level. For example, applying sleeping schemes to save energy will lead to a higher end-to-end delay.

Mobile robots on the other hand are high-end but expensive devices. They are generally equipped with GPS, a laser, cameras and computer ports. Although they also operate on batteries, it is easier to recharge robots at their base docking station than replacing the batteries of the sensor nodes. Recharging can be done after the robots performed their data muling task or when the helicopters fly back to their base.

These differences in storage, memory and processing create additional QoS challenges when applications are deployed over sensor-robot-sensor communication links. For instance, it is difficult to route high-bandwidth applications partly over a robotic network and partly over a sensor network. Furthermore, where sensor networks mainly suffer from packet loss and delay issues due to the limited resources and the unreliable links, mobile nodes create additional QoS challenges. Communication links are unpredictable due to mobile nodes and when mobile robots are involved in relaying information, delay issues arise in path planning and navigation algorithms.

3.2.3 Heterogeneous networks

Wireless sensor networks and robotic networks typically use different communication technologies and appropriate network protocols. For terrestrial sensor networks, 802.15.4 is used, while for robotic networks, 802.11 is used. But also networks deployed underwater, underground or aerial use different communication technologies. Furthermore, information can be exchanged between these different networks. For instance, underground or underwater collected information can be transported over a terrestrial robotic sensor network. Underwater networks are characterized by acoustic communication with very limited bandwidth, very long delays and a very high bit error rate [15]. Underground networks suffer from extreme path losses and low data rates [16]. These challenges should be taken into account when developing a QoS solution. It should not only work for each network individually, but also across different networks.

3.2.4 Heterogeneous applications

Wireless sensor networked robotics are used for many different applications in many domains. Applications cannot only differ per deployed robotic sensor network, but they can also evolve in time or different applications can concurrently run on the same network. Each application will have its own QoS requirements on delay, packet loss rate, throughput and packet delay variation. For instance, a robotic sensor network can be used for simultaneous reliable data collection and delay constrained voice and video monitoring. As a consequence, the network should be able to continuously adapt itself to the instantaneous application requirements.

4 Flexible QoS Framework

To meet the different QoS challenges and support the different QoS metrics, a flexible QoS Framework is designed and presented in the following section.

4.1 Requirements

Starting from the above challenges, the following requirements for the QoS Framework can be derived:

Adaptive The framework should be adaptive both in time and space. It should adapt itself in time to changing applications and dynamic environments due to mobile nodes or link breaks. It should also be adaptive in space because we aim at a generic QoS Framework that can be applied in different environments (terrestrial, underwater, underground and aerial).

Energy-efficient Since sensor nodes are often battery powered, replacing batteries is very time-consuming and to be avoided (especially in hard to reach environments). Energy is hence a scarce resource in wireless sensor networks. As a consequence, the QoS Framework should be designed with energy efficiency in mind, while the support of QoS tends to consume more energy. For instance, a lower delay will lead to shorter sleeping schemes and hence more energy consumption.

Scalable Sensor networks may contain thousands of sensor nodes. Therefore, the complexity of the designed framework should not grow considerably with the number of nodes.

Distributed Approach In a centralized network approach, a central control unit collects information, processes it and broadcasts the decisions or actions to the other (mobile) nodes. This behavior is not recommended in networks with thousands of nodes. Therefore, a distributed approach is desirable. Each node can take decisions locally and independently. However, a hybrid approach could also be beneficial, in which the robot nodes fulfill a centralized role in a limited area.

Support heterogeneity The framework should allow (1) different applications and should work on (2) nodes either applying existing (standardized) or new protocols. Furthermore, it should work for (3) each communication technology and (4) for nodes with different capabilities in terms of memory, processing and energy capacities. A lightweight framework can be used on nodes with low capabilities, while a more advanced framework implementation can be applied on nodes with more capabilities.

4.2 General QoS Framework

Fig. 2 shows the general approach of the QoS Framework. On top, a Network Application Aggregator is responsible for managing the different applications and for access control. Below, the general protocol architecture is shown. It contains the QoS Framework, the Information Database and the Core System. The QoS Framework contains a QoS Packet Policies, a QoS Protocol Policies and a QoS Management part. The Core System contains a Common Queue and the Network Protocols. Our QoS approach can be divided in a protocol-independent and a protocol-dependent QoS part, as will explained in more detail below.

The developed QoS Framework can be implemented in any existing network architecture, but is optimally suited for a cross-layer or layerless approach [17, 18].

4.3 Protocol-independent QoS support

The protocol-independent QoS support part is displayed in Fig. 3. The main components are the Information Database, the Common Queue, the QoS Packet Policies and the QoS Management.

The idea behind this protocol-independent approach is to provide QoS at an architectural level and thus extracting the QoS functionalities from the traditional layers/network protocols [19]. In a traditional approach, QoS needs to be supported at each network layer and each network layer has its own

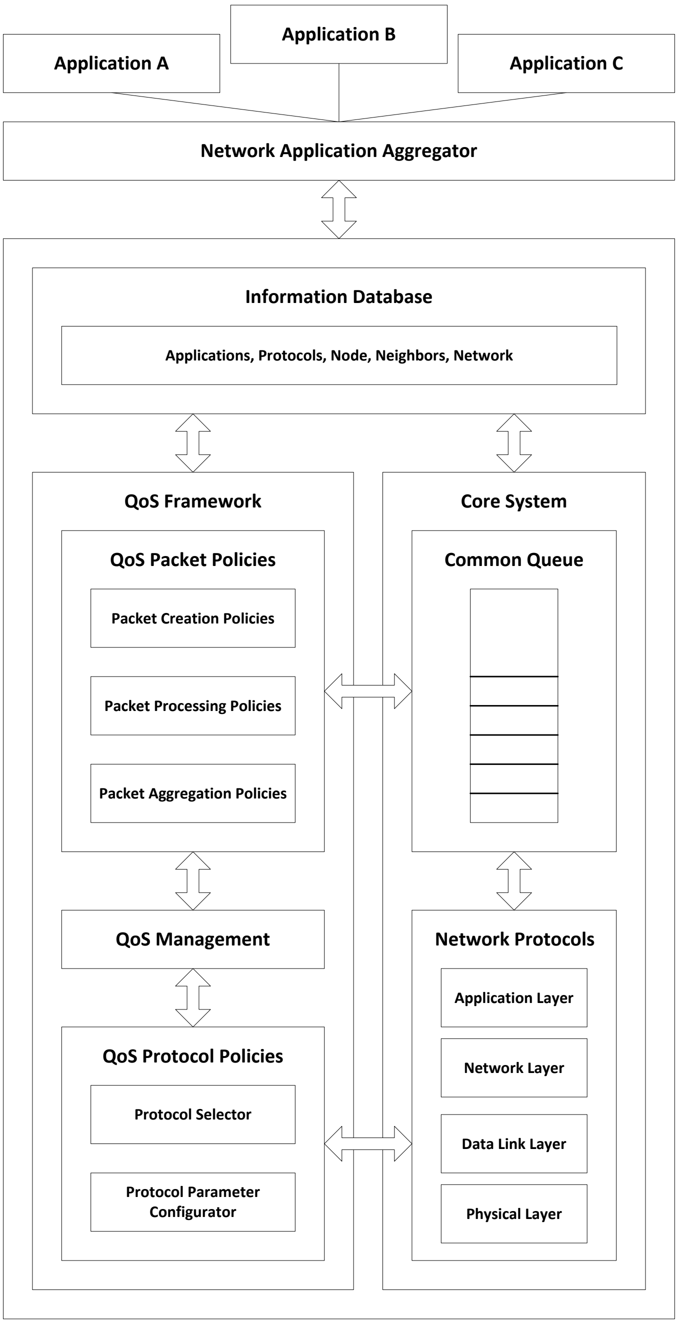

Fig. 2 General QoS Framework

storage queue. This approach leads to duplicate functionalities, a narrow per-

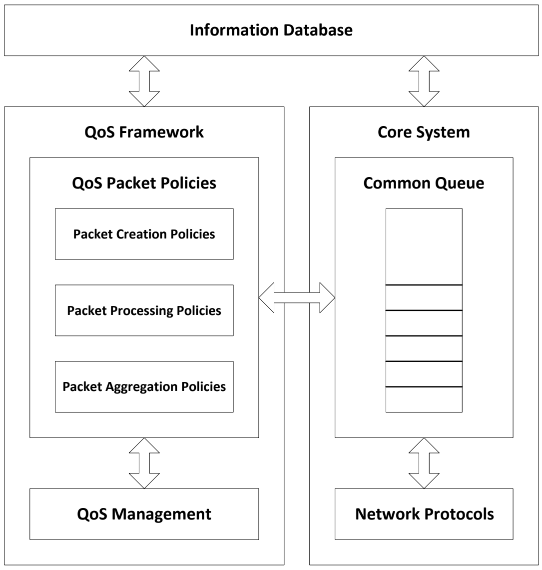

Fig. 3 Protocol-independent QoS support

layer view and a waste of scarce energy [20]. Introducing a separate information repository and working on a common queue has the advantage that the QoS system has a global network overview and that there is a load-balanced storage. A global network overview is beneficial when packets need to be dropped, or when the most suited packets for processing or sending should be selected. The load-balanced storage provides an overall optimal queue size, because high storage requirements for one layer can be compensated by a lower storage needed for another layer.

4.3.1 Information Database

The Information Database is responsible for storing metadata. For the protocol-independent QoS support part of the framework, the part of the applications is the most important one. Applications can register QoS-specific information on delay, packet loss rate, packet delay variation and throughput. Some examples are given in Table 1.

Table 1 Information Database

Network Protocol	**Parameter Name**	**Metadata Name**	**Metadata Value**
Monitoring Application	temperature	packet loss rate	20%
Voice Application	voice	end-to-end delay	200 ms

4.3.2 Common Queue

The Common Queue is responsible for storing the data packets. This can be incoming packets, locally created packets or packets that have to be forwarded. These packets are waiting in the Common Queue until they can be processed by the responsible protocol. On this Common Queue, several QoS mechanisms are applied, which are discussed below.

4.3.3 QoS Packet Policies

QoS Packet Creation Policies The QoS Packet Creation Policies are responsible for adding a QoS header to the data packets. This QoS header combines a mandatory QoS priority level and one or more optional QoS attributes.

Handling heterogeneous applications in wireless sensor networked robotics requires handling different traffic flows. Two QoS-oriented technologies that are common for traffic differentiation in IP networks are IntServ [21] and DiffServ [22]. IntServ is a flow-based approach which treats each flow individually. This approach is very flexible, but since each node has to maintain per flow state information, it is not scalable. The approach is also often too complex to use on sensor nodes with limited capabilities. DiffServ is on the other hand a class-based approach which differentiates between services by introducing some service classes using the DSCP field. The advantage is that complex operations move to the edge routers, while the core routers remain simple. The drawback is that quantitative information of each flow is lost after aggregation in service classes.

Our approach combines the best of both approaches:

- The simplicity and scalability of a class-based approach
- The flexibility of a flow-based approach

To realize this, a fixed amount of QoS priority levels are defined. To add more flexibility, optional QoS attributes can be added to each packet. These attributes fulfill fine-grained packet control within the limits of the chosen priority level.

In Table 2, a proposal for these QoS priority levels is given. The three highest priority levels are reserved for MAC, Routing, and Monitoring and Management control information. This prevent deadlock situations, for instance, it prevents that packets cannot be sent because the MAC protocol is not up and running. Furthermore, there is a distinction between real-time traffic, time-sensitive traffic and best effort traffic. Within the real-time traffic and time-sensitive traffic classes, a small distinction can be made between critical and default. This can be justified by the following example. Suppose two simultaneous voice calls are traveling through the network. One voice call is close to the maximum delay, while the other still has time left in order to arrive on time. The first call can then be given a higher priority in order to allow this call to arrive on time.

Table 2 QoS Priority Levels

QoS Priority Level	Description
7	Reserved (MAC control information)
6	Reserved (Routing control information)
5	Reserved (Monitoring/Management information)
4	Real-time traffic (critical mode)
3	Real-time traffic (default mode)
2	Time-sensitive traffic (critical mode)
1	Time-sensitive traffic (default mode)
0	Best Effort traffic

To differentiate between these QoS priority levels and make the approach flexible, additional QoS attributes can be added to each packet. Examples of these QoS attributes are given in Table. 3. When the application is not only time-sensitive, but also requires reliable data transport, a reliability-attribute can be added. The network protocols will then use these attributes to the best of their abilities. For instance, the MAC module can request an ACK message to ensure reliable transmission, and the QoS Framework can decide to drop a packet with a low reliability indication when the Common Queue is full.

Table 3 QoS Packet Attributes

Attribute	Description
Current_Delay	Traveled packet delay until now
Max_Delay	Max. allowed end-to-end packet delay
Reliability	Packet reliability indication

Note that the QoS Framework is responsible for setting the priority levels and attributes. The application or network protocol developer can only register its requirements in the Information Database.

QoS Packet Processing Policies The QoS Packet Processing Policies are responsible for diverse processing rules. First of all, they contain the packet selection rules. These rules define when a packet should be selected for processing and sending. This can be based on the priority level only, or also on QoS attributes such as delay and reliability when available. Secondly, the packet drop rules are defined. They define when a packet should be dropped and which packet should be dropped. For example, when the queue is completely full, it can drop the packet with the lowest reliability or a packet which deadline has almost reached and, as a consequence, has a high drop probability in one of the following nodes.

QoS Packet Aggregation Policies As already stated, energy is a scarce resource in sensor networks. Therefore, the QoS Framework has to implement a mechanism to reduce the consumed energy. Because in-network aggregation is a well known technique in sensor networks to reduce energy, the information aggregation policies defines when aggregation has to be performed. This aggregation is based on a trade-off between energy requirements and QoS requirements. More aggregation leads to a reduced energy consumption, but also increases the end-to-end delay.

These aggregation rules also define what should happen if packets with different QoS headers have to be aggregated. They can have a different priority level, but also different QoS attributes.

The Packet Creation, Packet Processing and Packet Aggregation Policies can be pre-defined (by performing a design time exploration study, from which we can determine the influence of decision parameters of the wireless system) or they can be defined at runtime through learning strategies, such as reinforcement learning [23].

4.3.4 QoS Management

The QoS Management is responsible for monitoring the information in the Information Database and, based on this information, defining/updating the Packet Creation, Packet Processing and Packet Aggregation Policies. For example, when the remaining energy of the node becomes low, less energy consuming aggregation rules can be selected. Another example is that the priority of the packets can be changed with changing application requirements. This way, a voice application with very stringent delay requirements can receive a (temporarily) higher priority level (from default mode to critical mode). It is also possible that packets needing a high-bandwidth communication path have to be processed first when a mobile node that can guarantee a reliable communication path to the sink comes within the reach of the node.

4.3.5 Discussions

The Information Database in which several application requirements can be stored, leads to an *adaptive* approach. QoS settings will be based on this information, and changing requirements in the Information Database leads to changing QoS settings. The QoS header defined in the QoS Packet Creation Policies and the Packet Processing Policies leads on its turn to *scalability* and *application heterogeneity* because each application can define its own specific requirements. Because this QoS header is sent together with the packet, a *distributed* approach is possible. Each node can take decisions based on this information and fulfill the packet's requirements to the best of its abilities. *Energy-efficiency* is met by adding QoS Packet Aggregation Policies. Because each node can implement (part of) the functionalities based on their capabilities, *node heterogeneity* is reached.

4.4 Protocol-dependent QoS support

The protocol-dependent QoS support part is displayed in Fig. 4. The main components of this part are the Information Database, the QoS Management, the QoS Protocol Policies and the Network Protocols.

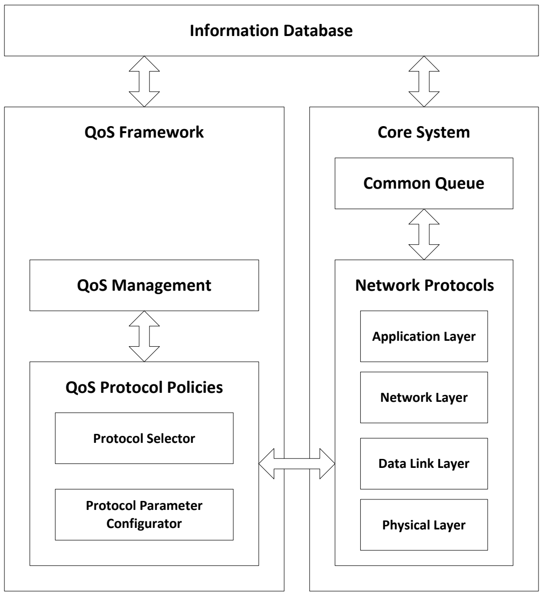

Fig. 4 Protocol-dependent QoS support

While the protocol-independent part decouples the QoS support from the network protocols, the protocol-dependent part interacts with the available (QoS-aware) network protocols.

4.4.1 Information Database

The Information Database has the same functionality as in section 4.3.1, namely storing metadata. For protocol-dependent QoS support, the information on protocols, nodes, neighbors and the network is used. For instance, the nodes and neighbors information database can specify if a node or neighbor is a mobile robot or a simple static sensor node, it can contain the amount and the position of neighboring mobile nodes and it can contain an indication of the remaining energy. This information can be used by the QoS Protocol Policies (see Section 4.4.2) when taking routing decisions. For example, a collection tree protocol that relays information to the sink will avoid mobile nodes that are passing by, as such nodes have less stable links. On the other hand, for high-bandwidth data, the high-capacity mobile nodes will be preferred for relaying this information. Furthermore, protocols can register information on the maximum QoS requirements that they can deliver (high reliability, low delay, ...) and information on the network density and the overall network performance can be available.

4.4.2 QoS Protocol Policies

The QoS Protocol Policies contain a Protocol Selector and a Protocol Parameter Configurator. These tools allow an optimal tuning of the network to the instantaneous QoS requirements. The Protocol Selector can select the most appropriate network protocol, for instance the DYMO [24] routing protocol for routing point-to-point voice traffic or a Collection Tree Protocol (CTP) [25] for routing monitoring information from different source nodes to one sink node. From the routing table (in case multiple routing protocols are available, this will be a shared routing table) and the neighborhood table, the Protocol Selector can select the most stable link or best routing path. This could be a direct neighborhood-link or a multi-hop routing path. Based on this information, the most optimal routing protocol can be selected.

The Protocol Parameter Configurator is responsible for an optimal tuning of the protocol parameters, for example, the optimal route time-out can be set for a routing protocol, or the MAC slots or the sleeping schedule can be tuned in an optimal way for a voice routing call.

As in the protocol-independent part, both the Protocol Selector and the Protocol Parameter Configurator can take decisions based either on pre-defined rules or on runtime learning strategies.

4.4.3 QoS Management

Comparable to section 4.3.4, the QoS Management is responsible for monitoring the information in the Information Database and defining/updating both the Protocol Selector and Protocol Parameter Configurator Policies. For instance, based on the load, the remaining energy of the network and the existence of mobile nodes, the most optimal routing and MAC protocols can be selected. The protocol parameters can be tuned to the instantaneous network condition or application requirements. For example, the MAC sleeping time can be tuned to the remaining energy level and to the requested QoS level.

4.4.4 Discussions

The possibility to tune and replace network protocols at runtime ensures *adaptivity* to changing environments and applications. Since an independent group of nodes in a certain area can decide to tune or replace the parameters, the approach is *distributed*. Protocol parameters can be tuned to the instantaneous optimal settings which leads to high *energy savings*. *Network heterogeneity* is reached since protocols can be tuned and replaced based on the network and communication technology.

5 Conclusions

Both mobile robotics and wireless sensor networks are booming research areas. Mobile robots are used in industry, military, health care and even in consumer products such as house cleaning and gardening. Wireless sensor networks almost have the same target region: monitoring environments, industry, health care and building automation. A relatively new research domain is integrating wireless sensor networks with such mobile robots. While sensor networks are used for large-scale monitoring, mobile robots are used for fine-scale operations such as detailed monitoring, deploying and maintenance of static nodes, and replacing human people in dangerous environments or providing help with tiresome tasks.

In this paper, we have shown that combining mobile robotics and sensor networks opens a new area of possible applications and that these applications often have stringent and diverse requirements on the delivered Quality of Service level. Since QoS support is already challenging in wireless sensor networks, adding mobile robots increases this challenge.

In order to cope with these QoS requirements, we have presented a generic QoS Framework that can be applied to existing network architectures. A basic QoS level can be guaranteed with a protocol-independent approach. It works independent of the available network protocols on sensor or robotic nodes. For a more in-depth QoS level, the protocol-dependent approach allows tuning of protocol parameters and replacing network protocols in a distributed manner. This way, the network can adapt itself to the instantaneous best QoS and network behavior.

This adaptive and modular QoS approach enables current and future QoS-aware network applications over wireless sensor networked robotics, so that they can be successfully integrated as part of our daily life.

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