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Review

A survey on cross-layer solutions for wireless sensor networks

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A B S T R A C T

Ever since wireless sensor networks (WSNs) have emerged, different optimizations have been proposed to overcome their constraints. Furthermore, the proposal of new applications for WSNs have also created new challenges to be addressed. Cross-layer approaches have proven to be the most efficient optimization techniques for these problems, since they are able to take the behavior of the protocols at each layer into consideration. Thus, this survey proposes to identify the key problems of WSNs and gather available cross-layer solutions for them that have been proposed so far, in order to provide insights on the identification of open issues and provide guidelines for future proposals.

Contents

1. Introduction

Wireless sensor networks (WSNs) have presented interesting and challenging issues since their creation. These networks have been drawing even more attention lately, mainly because of the plethora of different applications that have been emerging. Thus, they are the aim of many optimization proposals, and the cross-layer approaches have proved to achieve better optimization results than their layered counterparts. As several proposals have the same objectives, their efficiency comparison becomes important, and also as they consider different approaches, it is possible to discover which ones result in more gains to networks, avoiding complicated computation and excessive overhead. Furthermore, the mission of the WSN must be considered by the optimization proposal since, for instance, throughput maximization is not as important for an electrocardiogram (ECG) application as it is for video transmission. Finally, a look at the past of sensor networks can reveal the issues as they appeared, and also provide insights for the future challenges.

The first sensor networks have not considered wireless communication (Kohno et al., 1999). Moreover, wired systems have their own wired power supply, so energy consumption was not an issue at that time. The main concerns at the second-half of the

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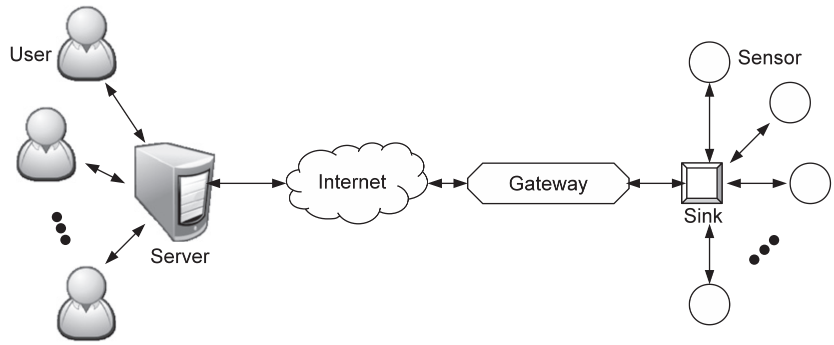

Fig. 1. Example of a wireless sensor network architecture.

1990s were on the manufacturing and packaging of sensors and actuators, ways of providing power supply to arrays of devices, internal and external communications (first steps towards wireless sensors), and signal processing (which is still an important line of research on the area) (Ko, 1996).

Nowadays, it is well known that the advances in radio technology have achieved a low power consumption level that allowed the creation of very small battery-powered communication devices. When joined with low-powered microprocessors connected to any kind of tiny sensors (*e.g.*, light intensity, temperature, 3D movement, heartbeat), a small battery-powered sensor, capable of processing data and communicating with other wireless devices is created. Furthermore, this new device allows the measurement of some phenomena that occur not only in a single point, but in a wide area. Finally, the sensed data can be communicated to one or more devices called sink nodes, which make the data available to a gateway, and further, to the user. Also, the user can change parameters of the sensor nodes (*e.g.*, measurement report intervals, sensor nodes topology) through the sink nodes. This scenario characterizes a WSN (Baronti et al., 2007), as depicted in Fig. 1.

However, WSNs can be deployed in different environments and for different purposes. Hence, they have received some particular denominations in the literature. For instance, sensor networks responsible for transmitting video and/or audio captured in an area, usually for surveillance purposes, may be called wireless multimedia sensor network (WMSN) or surveillance wireless sensor network (SWSN). Sensor networks deployed inside factories are called industrial wireless sensor networks (IWSNs) in the literature. When used for healthcare, they can be labeled wireless body area networks (WBANs). Furthermore, when the sensors are able to take actions according to predetermined conditions, the network may be called wireless sensor and actuator network (WSAN or SANET). And finally, if the sensors are not in fixed positions, they can be labeled mobile sensor networks (MSNs) if they cannot reach high speeds, or vehicular sensor networks (VSNs) if they are able to move at greater speeds. These characterizations of WSNs are useful to determine the different set of challenges that a sensor network may face. Thus, for instance, before reading about a solution designed for an IWSN, one can infer that interference from heavy machinery is going to be considered.

Nevertheless, some problems may arise in any type of WSN. For instance, although the components that assemble wireless sensors have been developed to save energy, sensor nodes consumption is still one of the main concerns (Akyildiz et al., 2007). The lifetime of a network must be enough for the mission of the WSN to be accomplished, thus protocols that waste this resource can make a network useless. Also, inefficient routing of packets can lead to waste of energy. A protocol that needs many routing advertisements will make use of sensors energy to send them, reducing the network lifetime (Choi et al., 2005). Moreover, the collaboration of nodes can help to reduce energy consumption by avoiding retransmissions when a packet does not reach its destination (Liang et al., 2007). Another problem, especially for WMSNs, is quality of service (QoS). Video packets cannot experience long delays, or the objective of the network may be compromised (Chen et al., 2007). Furthermore, wireless links are not reliable, especially for sensors since they are built with radios to save energy, and not for long range transmission. Thus, error control techniques are necessary, however they must also be energy efficient (Yu et al., 2007). Moreover, the capacity of the network is a parameter of interest. New sensors may be needed to extend the sensing area of a running WSN application. However, the impact of new nodes in the network must be studied or the performance of the whole network may be degraded (Liang and Liang, 2009). And like any wireless system, there is also the security problem. Cryptography can protect communication from eavesdropping, however the tradeoff between data protection and energy consumption must be studied (Misic, 2008). And finally, in order to enable WSNs to use contentionless medium access and coordinated sleep schedules, they need to be synchronized (Ye et al., 2005). All the solutions for the aforementioned problems conflict directly with energy saving, since the techniques to solve them require resources from one or more nodes. Thus, every proposed solution need to be energy efficient.

Cross-layer design states that parameters of two or more layers can be retrieved and/or changed in order to achieve an optimization objective. The concept of cross-layering has been first proposed for TCP/IP networks, when wireless links were deployed (Srivastava and Motani, 2005). Since the TCP/IP stack has been proposed for wired connections, there was a loss of performance when wireless technology became part of existing networks. Lately, cross-layering is a field that has been attracting more attention in WSNs research and it is still in its early development in this type of networks since it has not been deployed on many testbeds or networks yet (Misra et al., 2008). However, different solutions have already been proposed in the literature, and at least in numerical frameworks or simulations, they have proven to achieve better performance gains than their layered counterparts. Common goals of cross-layer optimizations in WSNs are reduction of energy consumption (Kulkarni et al., 2006), efficient routing (Choi et al., 2005), QoS provisioning (Yuan et al., 2006b), and optimal scheduling (Shu and Krunz, 2009), as can be verified throughout this work. Some of the most used protocols on cross-layer design and new protocol proposals are going to be presented, along with the optimizations they provide, in order to gather a small database on what has been proposed so far.

The goal of this survey is to show how cross-layer design has been adopted on wireless sensor networks (WSNs) to improve their performance by discussing the *state-of-the-art* literature on the subject. Also, open issues on cross-layering will be identified to facilitate the work of researchers towards further improvements applied to WSNs. Although Akyildiz et al. (2007) have assembled a comprehensive survey on wireless multimedia sensor networks and Yick et al. (2008) have done one for general WSNs, the aim of this paper is to gather and discuss cross-layer techniques proposed for all kinds of currently used WSNs.

The remainder of this paper is organized as follows. Section 2 provides an insight on the problems frequently addressed by cross-layer approaches. The protocols and techniques used on the studied solutions and new proposals are discussed in Section 3. Finally, in Section 4 the conclusions are drawn.

2. Drivers for cross-layer approaches

This section proposes to discuss the main problems addressed by cross-layer design for WSNs, pointing out the main one—energy consumption—and its relation to the other presented problems.

The most important advantage of wireless sensors is that they can be placed anywhere and measure phenomena that wired sensors cannot. To do so, wireless sensors need a source of energy, small enough to allow them to be placed in tight places, and even inside the human body. Thus, WSNs are power constrained, which makes sensors energy an invaluable resource. After the energy depletion of one or more nodes of a WSN, the application they were supposed to feed becomes compromised. Hence, the design of WSNs must be thoroughly thought in order to be energy-efficient.

According to Wang et al. (2008a), WSNs are mission-driven, which means that measurements of the behavior of a phenomenon will be carried out in an enclosed area. This fact can lead to redundancy since sensors placed near each other will make measurements with close values. Thus, transmitting correlated, or even repeated data is wasting energy. Moreover, sensor nodes will not transmit or forward packets all the time. Thus, keeping its functionalities turned on all the time is a waste of energy as well (Ha et al., 2006a,b).

Furthermore, the common metric to determine the lifetime of a WSN is the energy depletion of the first node of the WSN. However, this metric may not be precise when the running application tolerates a determined number of packet losses or a determined delay (Ozgovde and Ersoy, 2009). Thus, the lifetime of the network should be application-specific, and hence each different application must be studied to determine if the first node energy depletion is enough to characterize the lifetime of the WSN. If it is not, new metrics should be proposed.

The used routing protocol is tightly coupled with the WSN lifetime. A routing protocol might require the flooding of control packets to determine the routes, which induces an initial waste of energy. Also, topology changes are very likely to occur when considering WSNs, especially because of nodes that leave the network due to energy depletion. Furthermore, constant control messages exchange may be necessary to keep information about routes, adding transmission overhead and consuming sensors energy. Thus, from these problems it is possible to see that routing protocols for WSNs must be energy-aware and energy-efficient, adding the least overhead possible to avoid reducing the network lifetime to unacceptable thresholds (Zhang and Zhang, 2009).

WSNs are also used to measure mission-critical data (*e.g.*, video and/or audio for surveillance, health monitoring data for critical patients). Thus, transmission of data through these networks must cope with strict delay constraints and provide a suitable aggregate throughput. It is worth noting that these QoS requirements conflict directly with energy consumption issues since they may require the use of more transmission power to reduce the occurrence of channel errors and a more frequent access to the medium (Melodia and Akyildiz, 2010). Hence, the tradeoff between QoS and energy consumption must be thoroughly studied.

Since wireless media are used to transmit data, packets are subject to interference from other transmission, resulting in errors. This issue is closely related to energy constraints, since packet errors will cause retransmission, requiring more energy from the sensor. Moreover, retransmission will affect delay and data throughput, also affecting QoS. The use of error control techniques can prevent retransmission, however at the cost of introducing some transmission overhead, and thus increasing the sensors energy consumption. Hence, it can be seen that transmission errors, QoS constraints, and energy consumption are closely related, requiring cross-layer solutions to address these problems simultaneously (Vuran and Akyildiz, 2009). Also, the effects of the use of automatic repeat request (ARQ), forward error correction (FEC), and their combination on the discussed parameters should be studied to find an optimal solution for WSNs.

The number of sensors in the network can affect the performance of the whole network (Olariu and Xu, 2005). In a WSN made of only a few sensors, more energy will be used to reach the other nodes, thus reducing the network lifetime. Also, the farthest sensors may become isolated from the rest of the network when the relay node they depend on has no battery left. On the other side, in a WSN with too many sensors, coverage and energy consumption to reach other nodes will not be an issue (Habib, 2007). However, the forwarding of messages may cause congestion and an energy-efficient routing becomes complex to be calculated. Hence, the capacity planning of a WSN is an important design parameter to be considered for efficient use of its scarce resources.

Given the broadcast nature of the wireless medium, sensor nodes in WSNs become a potential target for attacks (Chen et al., 2010). Malicious nodes can join the network and eavesdrop in order to damage transmissions or steal information. Some attacks have been identified in the literature and also some attack detection and protection techniques have been proposed.

One common type of security breach is the spoofing attack. It is not difficult to find out a node identification in a wireless network. Just by capturing packets on the air may allow a node to discover a valid node address. Hence, the malicious node can change its address to the valid captured one and start transmitting false data into the network (Chen et al., 2010). In WSNs, the Sybil attack is more damaging. In this case, an attacker assumes multiple network identification and starts broadcasting messages, thus disrupting routing and preventing the network from working properly.

Another type of attack is the wormhole attack. Its goal is to capture traffic from one part of the network and retransmit it in another. The traffic can be captured by a malicious node and transmitted to another through a different communication link (*e.g.*, wired link, different wireless band or technology). Then, the second malicious node replicates the captured traffic to its neighbors in order to interfere with routing protocols.

Cryptography can also be used for packet exchange safety. However, cryptographic keys must be exchanged beforehand to enable nodes to encrypt their messages and also more processing resources will be necessary to encrypt and decrypt data. This process consumes precious energy from the sensors (Misic et al., 2006a), making the tradeoff between network security and energy consumption clear.

The sensors hardware clock reference can directly affect an application operation. For instance, a WSN for target detection is useless if it cannot register both the position and the detection time of an event (Cheng et al., 2009a). This shows once more the application layer dependence on the physical layer. However, the complexity of the used synchronization protocol can directly affect the network lifetime (Ganeriwal et al., 2009). Hence, the network time protocol (NTP), used for synchronization on the Internet, could not be used in WSNs, and then three (non-cross-layer) approaches have been defined for the proposal of new synchronization protocols—sender to receiver synchronization (SRS), receiver to receiver synchronization (RRS), and flooding. The flooding time synchronization protocol has been proposed according to the latter category, and it can be inferred that this technique is not energy-efficient. Furthermore, the timing-sync protocol for sensor networks (TPSN) and the tiny synchronization/mini synchronization (TS/MS) protocols that belong to the SRS category require that sensor nodes receive and transmit once to achieve synchronization. Although it is more energy-efficient than flooding, where duplicate transmissions may occur, it still wastes some energy. Finally, in the RRS category, the reference broadcast synchronization (RBS), the pairwise broadcast synchronization (PBS), the network-wide pair selection algorithm, and the group-wise pair selection algorithm (GPS) have been proposed. In these proposals, some sensors take advantage of the broadcast medium to overhear the synchronization transmission between other nodes, saving transmission resources (Cheng et al., 2009a). Nevertheless, none of the mentioned are cross-layer proposals, acting on the synchronization regardless of the application. Thus, a tradeoff between synchronization accuracy and sensors energy consumption can be achieved if the required application quality of service is taken into account.

From the discussion presented in this section, it can be seen that all limitations of WSNs are connected. Also, routing, QoS constraints, security, and time synchronization conflict directly with sensors energy consumption, requiring a comprehensive study to identify the existing tradeoffs. Thus, in order to tackle the problems interdependence, a cross-layer solution is needed. Clearly, these proposals are more complex than the non-cross-layer ones. However, energy consumption must be reduced at all costs in these networks, or else they will not operate for the extended periods they are supposed to. The ideal cross-layer solution—but also the most complex—would involve parameters from all layers of the stack since all of them affect energy consumption to some degree. Hence, the increase in the sensors design complexity is inevitable and inversely proportional to the sensors energy capacity.

3. Considered technologies at each layer

Differently from the conventional networks layers, WSNs consider only the following layers (Baronti et al., 2007): application (APP), network (NWK or NET), medium access control (MAC), and physical (PHY). Although there is no transport layer, since it is complex and it would waste sensors energy (Misra et al., 2008), some WSN protocols have been designed for congestion control and reliable end-to-end communication (functions of the transport layer). Some of them are presented below, in the Network layer subsection. Nevertheless, some authors defend the definition of a transport layer on WSNs (Misra et al., 2008), keeping the same layers stack as defined by TCP/IP. The considered stack can be seen in Fig. 2 with two examples of cross-layer interactions. For instance, the QoS requirements at the application layer can be informed to the MAC layer in order to achieve better scheduling for the running application, and the channel state information (CSI) can be fed to the network layer so the routing protocol can avoid paths including channels in a bad state.

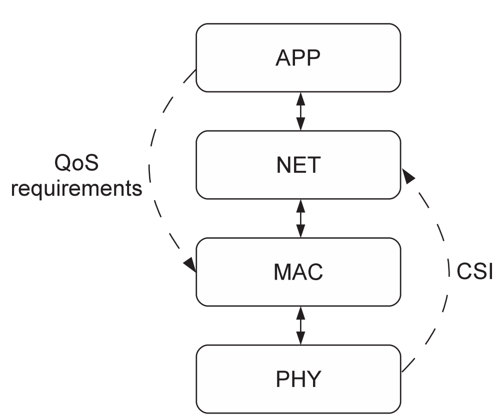

Fig. 2. Considered layers stack with two examples of cross-layer interactions.

Table 1 summarizes the technologies, protocols, and schemes considered by the cross-layer proposals in the same order as commented in the following subsections. It is worth noting that some cross-layer proposals are mathematical frameworks that consider a set of parameters at each layer, however without using any specific technology or scheme at the considered layer. Thus, a cross-layer proposal may have a technology or scheme represented at only one layer in Table 1.

3.1. Application layer

MPEG and H.26 are the most used compression standards for video. The compression they provide allows more video to be stored and less bandwidth for video transmission is required (Chen et al., 2006b). Chen et al. (2006b) have proven that the IEEE 802.15.3 technology is not suitable for variable bitrate (VBR) video transmission. Hence, they have proposed the energy diffserv application-aware scheduling (EDAS). This cross-layer algorithm increases the quality of the received video by increasing the fraction of decodable frames to more than 85%, while the IEEE 802.15.3 achieves a worst case of 65%. Moreover, energy consumption is reduced up to 30% by compressing video with lower quality where QoS admits it, thus transmitting less data, and transmitting higher video quality where QoS constraints are stricter. Also, EDAS includes an admission control mechanism to provide the necessary QoS to all the video flows in transmission.

Yuan et al. (2006b) have proposed a cross-layer solution to increase the lifetime of clustered WSNs. The QoS parameters are taken into account by the adaptive code position modulation scheme (ACPMS) at the cluster heads, adapting the transmission according to the computed BER. Intra- and inter-cluster QoS performance is assessed through simulation, proving that QoS is provided in terms of delivered packet ratio and end-to-end delay and that the first node death is delayed at least for 60 rounds, where the rounds are the moments when the clusters are rebuilt.

Chen et al. (2007) have proposed another solution to save energy in WSNs transmitting H.26L videos. The proposed cross-layer routing scheme called directional geographical routing (DGR) breaks a video transmission in several flows that are transmitted through different routes in order to avoid energy depletion of nodes in a single route. Also, FEC is used to protect the multiple video flows on their path to the sink node, helping to guarantee the entire video arrival.

Disregarding the type of data generated by the sensors, but still considering the application layer, data source coding (DSC) is a technique used to encode application data in order to reduce the amount of transmissions in a network. For instance, sensors deployed close to each other may measure values that do not differ much. Hence, each sensor encodes its measurement using fewer bits than it regularly would, making it impossible to retrieve the measurement value with information from only one node. However, when all measurements reach the sink node, it can combine the sensors encoded data to retrieve the values measured by all the sensors. Thus, fewer bits are transmitted and energy is saved. Wang et al. (2008a, 2009) have proposed cross-layer solutions to transmit data using DSC combined with multiple transmission rate medium access protocols. In Wang et al. (2008a), multi-level rate routing (MLRR) is proposed, while in Wang et al. (2009) quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) are considered. Both proposals are

Table 1
Main technologies, protocols, and schemes considered in cross-layer proposals.

Proposal	Authors	Technologies and/or schemes at each considered layer			
		Application	Network	MAC	Physical
EDAS	Chen et al.	MPEG-4	–	EDAS	–
–	Yuan et al.	–	Cluster-based routing	ACPMS	ACPMS
DGR	Chen et al.	H.26L / FEC	DGR	–	–
MLRR	Wang et al.	DSC	MLRR	Rate assignment	CSI/REI
–	Wang et al.	DSC	–	–	QPSK/QAM
–	Liang et al.	Data fusion	–	TDMA/TDD	16-QAM/CSI
GRASS	Karaki et al.	–	GRASS	–	–
CEDA	Choi et al.	–	CEDA	802.11-based	–
EDDD	Chen et al.	RT-/BE-traffic	EDDD	S-MAC	–
PCCP	Wang et al.	–	PCCP	CSMA-like	–
GMREE	Sanchez et al.	–	GMREE	–	–
A-MAC	Nam et al.	–	AODV	A-MAC	–
APRMAC	Mitchell et al.	–	One-hop neighbors discovery	APRMAC	–
–	Cheng et al.	Data aggregation	–	TDMA	Transmission power control
CAGIF	Zhang and Zhang	–	CAGIF	CDMA	–
XLCU	Melodia and Akyildiz	–	GIF	TH-IR-UWB	UWB/dynamic channel coding
–	Shi et al.	–	Minimum-energy routing	–	UWB
–	Shi and Hou	–	–	–	UWB/Transmission power control
–	Liang and Liang	–	–	–	Virtual MIMO
	Yuan et al.	–	–	CSMA/TDMA	Virtual MIMO
	Misic et al.	–	–	CSMA/CA	Duty cycles
CAEM	Lin and Kwok	–	LEACH	CSMA/CD	Duty cycles/CSI
SS-Trees	Ha et al.	–	–	CSMA	Duty cycles
–	Misic	–	–	CSMA/CA	BPSK/O-QPSK/Duty cycles
EX-MAC	Hong and Kim	–	–	EX-MAC	–
ENCO	Demirkol and Ersoy	–	–	Contention-based	Duty cycles
–	Kwon et al.	–	based/ARQ	TDMA-power control	Transmission
–	Mao et al.	–	–	TDMA-based	-
–	Madan et al.	–	–	TDMA	–
–	Cui et al.	–	–	TDMA	M-QAM
–	Su and Zhang	–	–	TDMA	CSI/M-QAM/battery discharge dynamics
–	Shi and Fapojuwo	–	–	TDMA	FSK
–	Phan et al.	–	–	TDMA	–
–	Wang et al.	–	–	TDMA-based	–
–	Shu and Krunz	–	–	Hybrid TDMA/CDMA	–
CLPC	Messier et al.	–	–	ALOHA/ARQ	CLPC
DOMRA	Miao et al.	–	Two-hop knowledge	ALOHA	CSI
DQBAN	Otal et al.	–	–	DQBAN	–
DPLM	Chen and Zhao	–	–	–	CSI/REI
TM-MAC	Ren and Liang	–	–	TM-MAC	UWB
LEMMA	Macedo et al.	–	–	LEMMA	–
TC-MAC	Kim and Park	–	–	TC-MAC	Duty cycles
–	Chehri et al.	–	–	TH-IR-UWB	Transmission power control/UWB/Duty cycles

able to calculate the best transmission rate to achieve low packet error rates.

Data fusion (also known as data aggregation) is a technique used to reduce measurement errors. In this case, data are not encoded to reduce the number of transmitted bits. Instead, data received from several sensors are compared to search for errors. Thus, a reliable approximation of the measured phenomena is achieved. Liang et al. (2007) have proposed a cross-layer solution to enhance data fusion and the network lifetime. They have used sensors channel state information (CSI) to schedule transmissions only to the sensors experiencing better channels, and they have also used this information to weight the reliability of a sensor measurement when performing data fusion. Hence, preventing sensors experiencing bad channels from transmitting, the bit error rate could be reduced up to 1000 times when compared to the maximum ratio combining fusion algorithm, thus wasting less energy.

Data aggregation has also been used by the GRASS protocol, proposed by Al-Karaki et al. (2009). In the analyzed scenario, clusters are formed and the cluster heads (CHs) aggregates the data coming from the sensors in the cluster. Then, the CHs are responsible to find a route to the base station that maximizes the network lifetime. Results have shown a gain of at least 35% on the lifetime when compared to the directed diffusion protocol. Also, to avoid limiting the network lifetime to the CHs lifetime, new CHs are elected periodically inside each cluster.

3.2. Network layer

Routing protocols attract special attention by their impact on the network lifetime. One of the most quoted architecture by routing proposals for clustered WSNs is LEACH (low-energy adaptive clustering hierarchy) (Heinzelman et al., 2002). In this proposal, the network is divided in clusters, and cluster heads (CHs) are randomly chosen inside a cluster every round, guaranteeing that all the nodes in the cluster have the opportunity of being the CH and thus sharing the energy consumption among all nodes. The proposal has proven that for the same amount of sensors initial energy, the proposed protocol can transmit 40% more data than when using LEACH.

A cross-layer routing protocol for WSNs proposed by Choi et al. (2005), the cell based energy density-aware (CEDA) protocol, considers the division of the WSN in cells, extending LEACH to multihop routing inside cells. The routing tables include one more variable—the energy level from the neighboring nodes. Then, the energy level information is used as a weight factor when routing data, avoiding the nodes with less remaining energy. Hence, the routing protocol has proven that only 5% of the nodes have their energy depleted when all the nodes are dead using the AODV protocol.

The directed diffusion routing protocol has been extended by Chen et al. (2006a), since its use has not shown to be adequate for WSNs. Their proposal, the energy-efficient differentiated directed diffusion (EDDD), is able to differentiate between real-time (RT) and best effort (BE) flows. Hence, RT flows are routed considering their end-to-end time constraints, while BE flows are routed in an energy-efficient manner. Also, route-repairing techniques improve the ones used by directed diffusion, reducing the time to reroute RT flows in case of node failure. Their results have shown that the network lifetime is increased when compared to directed diffusion.

Wang et al. (2007) have proposed a cross-layer priority-based congestion control protocol (PCCP) for WSNs. Although congestion control is a function of the transport layer, this work addresses the congestion problem from the network layer. The proposal includes two new queues between network and MAC layers—one for traffic originated at that node and another for the traffic routed through the node. By verifying the inter-arrival packet times in the routed traffic queue, PCCP is able to detect congestion. Then, implicit congestion notification (ICN) is used to inform the congestion to the other nodes. Finally, each node reduces its traffic routing queue-scheduling rate to control the detected congestion. The results presented in the work show that the normalized network throughput is stabilized above 90% and the fluxes are fairly scheduled.

The energy-efficient geographic multicast routing (GMREE) has been proposed by Sanchez et al. (2007) to reduce the energy consumption in SANETs. For that, they have created the cost over progress ratio, a metric that informs the cost (energy amount) of reaching a neighbor and the progress it provides towards a destination. Thus, multicast trees are formed according to that metric with the objective of reducing energy consumption. Results show that GMREE is able to reduce energy consumption in multicast SANETs by 10 times when compared to the IPowerProgress algorithm.

In the cross-layer design proposed by Nam et al. (2007), their new adaptive MAC (A-MAC) requires a change in the used routing protocol. New metrics that depend on the duty cycle (the rate between a sensor active and sleep times) influence the routing decisions. The authors have chosen the ad hoc on-demand distance vector (AODV) routing protocol for their tests. A-MAC changes the nodes duty cycle dynamically to achieve a predetermined network lifetime. Thus, AODV routes the packets according to the adopted metrics in order to verify the behavior of end-to-end delay and network lifetime. Their results have shown that the common routing metric (minimum hop count) is more energy-efficient when combined to A-MAC, however the delays are higher. The other metrics implemented on AODV can reduce delay, but they are less energy-efficient, showing that there is a tradeoff between energy consumption and delay.

Mitchell et al. (2010) have proposed the aerial platform based routing and medium access control (APRMAC). In this protocol, each sensor node needs to discover their one-hop neighbor through sending *hello* packets. Then, all sensors send this information to an aerial node in LOS with all the sensors. The aerial platform is responsible for calculating the routes from all the sensors to their nearest sink nodes, and then it schedules medium access time for all the nodes. Thus, each node knows when it can transmit, when it is supposed to listen, and when it can enter *sleep* mode, saving at least 5% more sensors energy than TRAMA. Figure 3 shows an example of an APRMAC scenario.

Cheng et al. (2009b) have argued that shortest path or minimum energy routing solutions have not considered the bandwidth constraints of WSNs. Thus, they have proposed a cross-layer routing protocol that is able to adjust the time division multiple access (TDMA) link rates according to their utilization. It has been proven in their work that the lifetime of the network is increased by 40% when compared to shortest path routing and the capacity of the links is respected.

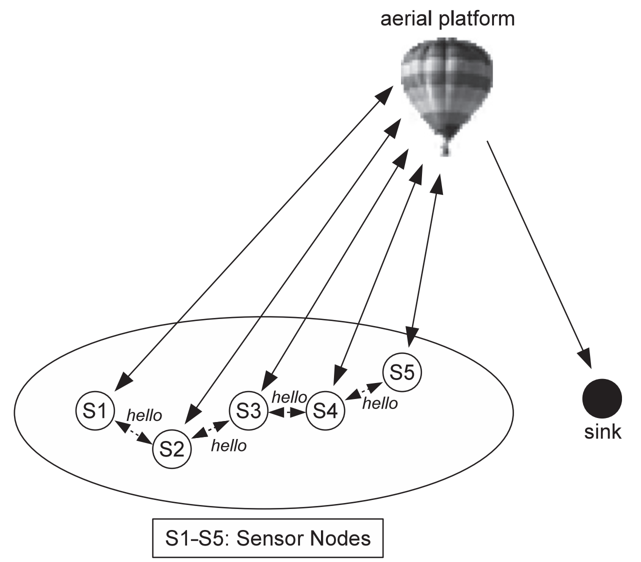

Fig. 3. Example of an APRMAC scenario (Mitchell et al., 2010).

A new routing metric has been defined by Zhang and Zhang (2009) for their cross-layer channel-aware geographic informed forwarding (CAGIF) protocol. The efficient-advancement metric (EAM) determines the optimal relay node position to reach the next hop towards the destination. They have considered CDMA as medium access method, also taking interference into account. Through the use of the EAM and three positions (the current node, the source, and the destination), CAGIF provides routing with at least 50% less energy consumption and up to 4 times less packet control overhead when compared to GIF.

Melodia and Akyildiz (2010) have proposed a cross-layer control unit (XLCU) to provide QoS for WMSNs. They have considered geographical forwarding to control the flows and hop-by-hop QoS requirements. Also, the XLCU controls the scheduling and rate assignment of the time hopping impulse radio UWB (TH-IR-UWB), preventing collisions and idle listening. Thus, throughput and reliability are increased and delay is reduced, according to the results.

A centralized nonlinear programming problem for optimal routing, scheduling, and power control has been defined by Shi et al. (2006). For large networks, a heuristic algorithm for the optimization problem was proposed. In a later proposal by Shi and Hou (2008), they have included rate assignment to the optimization problem and then derived closed-form expressions to calculate the capacity of the WSN.

Liang and Liang (2009) have proposed a maximum spanning tree searching (MASTS) algorithm to determine the best set of nodes when creating virtual multiple-in multiple-out (MIMO) links in order to connect the routes determined by the routing protocol. Although a specific routing protocol has not been considered, implying that the nodes already knew the routes, the authors have proven that the bit error rates experienced by the users is reduced up to 10 times when compared to regular virtual MIMO communication.

Yuan et al. (2006a) have also considered MIMO communication in their cross-layer proposal. They have considered the LEACH protocol as base for multicluster routing. The cluster heads (CHs) are responsible for choosing the nodes that will be participating in the MIMO communication to the next cluster head. This is done by achieving the minimal acceptable packet error probability, according to the end-to-end QoS parameters. Thus, avoiding packet retransmission minimizes the overall energy consumption.

3.3. Medium access control layer

Cross-layer designs that do not consider an optimization involving the medium access control layer are rare in the literature. The large number of proposals in this subsection proves this statement. These proposals will be briefly discussed, emphasizing the considered technologies used for optimization.

Carrier sense multiple access with collision avoidance (CSMA/CA) is the medium access technique used by IEEE 802.15.4. Misic et al. (2006b) have considered this technology in their cross-layer activity management scheme. The sensors duty cycles (*sleep* and listen/transmit time) are calculated in order to achieve a determined event sensing reliability. This is done according to the packet loss probability, calculated with physical layer measurements, and packet collision probability, packet blocking probability, and service time probability distribution, measured at the medium access layer. Two scenarios were considered for duty cycle calculations—centralized and distributed. For the centralized scenario, the sink node determines the duty cycles and transmits them to the other sensor nodes. This method achieves the required reliability, but it can deplete the coordinator node energy faster. On the distributed case, the coordinator only sends the number of alive nodes to the sensors, and then each of them can calculate its own duty cycle to keep the reliability above the predefined limit. Thus, the coordinator node consumes less energy and the network event sensing reliability is kept at the same level.

Lin and Kwok (2006) have proposed CAEM, a cross-layer energy management approach considering carrier sense multiple access with collision detection (CSMA-CD) as channel access method. All sensors continuously sense the channel state. If one of them has a packet to be sent, it is done if the channel is in a good state. If not, the packet is buffered, the sensor enters *sleep* mode, and a fair scheduling and queuing algorithm avoids starvation in case the channel stays in the bad state for a long time. Thus, the lifetime of the network is increased up to 40% when compared to pure LEACH through the knowledge of the channel state.

According to Ha et al. (2006a), pure CSMA is preferred over contentionless methods, *e.g.*, code division multiple access (CDMA) and time division multiple access (TDMA) because it is simpler to be implemented, and over CSMA/CA because the latter adds overhead to transmission. Hence, Ha et al. (2006a) have proposed the sense-sleep trees (SS-Trees) where trees of sensor nodes are organized to facilitate the sensors sleep scheduling. Then, transmitting nodes access the medium using CSMA, and through the use of downstream and upstream phases, the number of packet collisions is reduced. Thus, they have achieved reduced energy consumption while meeting the surveillance requirements.

Another advantage of CSMA/CA over TDMA is its capability of handling communication among a large number of sensors (Misic, 2007). Based on this, Misic (2007) has modeled the lifetime of a multilevel clustered IEEE 802.15.4 WSN. The effect of the number of sensors in each cluster on the network lifetime is analyzed by using the model, validated through simulations. Finally, results show that adjusting the number of nodes in each cluster can increase the lifetime of the network.

Proposed to reduce end-to-end latency when duty-cycles are considered for energy consumption reduction, express MAC (EX-MAC), designed by Hong and Kim (2009), considers CSMA/CA as multiple access method. When multiple sensors sense an event, event data reservation (EDR) is used to schedule transmissions along the path to the sink in order to reduce end-to-end delay. EX-MAC has also proven to be more energy-efficient than previous multiple access proposals, achieving up to 15 times less energy consumption than X-MAC.

A new medium access metric, the estimated number of contenders (ENCO), has been proposed by Demirkol and Ersoy (2009). They have considered CSMA as the multiple access method and they have discussed the effect of the number of nodes contending for the channel on the end-to-end delay. As a result, they have managed to reduce contention delay by calculating and feeding the sensors with each ENCO value before the network operation. Results have shown that the end-to-end delay and energy consumption are reduced when compared to the traditional contention method.

Despite the commented advantages of CSMA over TDMA, authors of cross-layer proposals also consider TDMA because of its simpler deterministic analysis and transmission guarantees. Kwon et al. (2006) have proposed a cross-layer routing, automatic repeat request (ARQ), and power control scheme considering TDMA method at the MAC layer. The centralized algorithm verifies the channel state at every link. Then, it can define the best routes for each information stream, also adapting the retransmission limits to increase the probability of successful packet delivery. Hence, a tradeoff between the packet delivery probability and the network lifetime is respected.

TDMA has also been considered in the cross-layer proposal by Mao et al. (2007). In this proposal, the authors schedule all available transmission slots in an optimal manner by using a combination of two algorithms—particle swarm optimization (PSO) and hybrid algorithm (HA). The results shown in the work prove that the proposed combined algorithm reduces the energy consumption for TDMA slots allocation by 17% when compared to max degree first coloring algorithm and by 5% when compared to the node based scheduling algorithm.

Madan et al. (2006) have considered TDMA in their cross-layer proposal as well. They have proposed their own routing scheme and they have also considered a generic multilevel modulation as transmission method of the interfering nodes. Then, their cross-layer algorithm calculates the optimal routes to balance the network load, the best slot scheduling for TDMA, and the optimal modulation scheme in order to reduce interference and transmit using lower power. Thus, results have shown that the WSN lifetime is increased by 7 times when compared to optimal TDMA.

The joint optimization of network, MAC, and physical layers has been proposed by Cui et al. (2007). At the physical layer, M-ary quadrature amplitude modulation (MQAM) is considered. The modulation adapts to the channel conditions by increasing its transmission rate (also increasing BER) when the channel is in a good state and decreasing it to be more robust when the channel is in a bad state. The MAC layer schedules more TDMA time slots to the links with less transmission rate to keep the throughput, and the network layer reroutes traffic to the links with better channel states. By solving the mathematical optimization problem considering these parameters, the proposal is able to reduce sensors energy consumption.

Su and Zhang (2009) have proposed a cross-layer battery-aware TDMA MAC protocol for WBANs. They have studied battery dynamics, concluding that the energy of a battery takes longer to be depleted if its use is subject to idle times. Thus, their proposal schedules transmissions keeping a node from transmitting for the longest possible time, however respecting QoS constraints. Also, adaptive modulation is considered to reduce packet losses due to the channel varying characteristics with time. Their analytical model has been validated through simulations considering an ECG sensors application. Their tests have proven that the number of packets transmitted in the network is increased by up to 50 times when compared to IEEE 802.15.4 and by up to 33 times when compared to Bluetooth, while QoS constraints are respected for both cases.

The cross-layer nonlinear optimization model proposed by Shi and Fapojuwo (2010) considers TDMA as medium access method. The mathematical framework collects information on the traffic load, the retransmission and modulation scheme, and the bit error rates to calculate the optimal transmission powers and the flow rate used for each link. By the analysis of the trend of the calculations with the nonlinear optimization model, an algorithm for minimum delay scheduling has been proposed. The algorithm has been tested on linear, grid, and random topologies, proving to be energy-efficient.

Node admission and reduction of the energy consumption in WMSNs are the goals of the solution proposed by Phan et al. (2009). They have considered that sensor nodes access the medium through the TDMA method and that their speed ranges from static up to low mobility. They have formulated a mixed-integer linear programming (MILP) problem for network lifetime maximization with node admission. Then, they have shown the effect of the nodes transmission bandwidths on the number of admitted nodes and the network lifetime.

A TDMA-based MAC protocol is part of the cross-layer model proposed by Wang et al. (2008b). Power control, link access, and routing are considered in their mathematical model to satisfy the Karish–Kuhn–Tucker (KKT) optimality conditions. The presented results have shown that the derived equations provide an upper bound for the network lifetime, validated through simulations.

Shu and Krunz (2009) have proposed a cross-layer solution considering hybrid TDMA/CDMA medium access method. First, intercluster interference is avoided by allocating different *superframes* (sets of TDMA frames) to interfering clusters, medium access known as spatial TDMA (STDMA). Thus, when nodes transmit in a cluster, adjacent interfering clusters will not transmit at the same time. Second, CDMA scheduling is allocated to sets of sensors inside each cluster according to a power and time control (PTC) in order to reduce power consumption inside the clusters. Through the combination of those techniques, the network lifetime is increased, according to their results.

Some cross-layer proposals have also considered ALOHA as medium access method. This has been the medium access method studied by Messier et al. (2008), combined with an infinitely persistent ARQ. They have proposed a cross-layer power control (CLPC) algorithm that is capable of calculating the best received power for each node (and thus optimal transmission power can be calculated) taking the multiple access interference (MAI) into account. Simulation results have shown energy savings of up to 74% when compared to noise CLPC.

ALOHA medium access method has been considered by Miao et al. (2009) in their cross-layer proposal as well. In order to derive the equations for decentralized optimization for multichannel random access (DOMRA), they have also considered that some nodes are out of the range of others, differently from other channel-aware ALOHA proposals considering that all nodes interfere with each other. Through the collection of traffic information from neighbors and instantaneous CSI measurement, transmission power is allocated to every sensor node in order to reduce interference and increase network utility and transmission fairness.

The distributed queuing body area network (DQBAN) is a cross-layer solution proposed by Otal et al. (2009). Transmission of a packet is scheduled according to a fuzzy-rule based on the QoS constraints of the packet and the current traffic. Thus, a packet is sent through slotted ALOHA medium access method when the traffic is light, a reservation protocol is used if the traffic is heavy, and a polling scheme is used if delay constraints are tight and cannot afford collisions. Their proposal has shown to reduce WBAN energy consumption up to 100,000 times and increase the packet delivery rate by up to 42.75% when compared to distributed queuing without energy policy, and decrease mean packets delay by 8% when compared to distributed queuing without scheduler.

Chen and Zhao (2007) have identified two important physical layer parameters that should be used by MAC protocols—the channel state information (CSI) and the residual energy information (REI). The proposed medium access protocol schedules transmission to the sensors that experience a good channel when the sensor nodes have full energy, and when part of the sensors energy has been used, the scheduling prioritizes the sensors with more energy left in order to even the nodes energy. Thus, the energy consumption of the WSN is reduced by 8 times when compared to the pure conservative scheme.

Ren and Liang (2008) have proposed a new cross-layer medium access method—the throughput maximized MAC (TM-MAC). It is able to divide ultra-wideband piconets in sets and to calculate the optimal scheduling and transmission rate in order to minimize interference. Results have shown that throughput is increased by up to 22% and that packets transmission time is reduced by up to 32% when compared to the IEEE 802.15.3 performance.

The latency-energy minimization medium access (LEMMA) is a cross-layer proposal by Macedo et al. (2009) that jointly optimizes routing in sporadic-traffic WSNs. Transmission of higher power tones is used to avoid scheduling of sensors at the same time slot of the TDMA method. When a tone from a node is received, no other sensor attempts to occupy the time slot. This has proven to reduce transmission interference in the considered lognormal shadowing scenario. Thus, it has been shown that delay is reduced by 12 times and the network throughput is increased by up to 28% when compared to LMAC.

Some proposals that make use of listen and sleep schemes (duty-cycles) cause an increase in the end-to-end latency and a reduction of the network throughput. Furthermore, the high number of nodes in WSNs may result in congestion near the sink nodes (Kim and Park, 2009). To solve these problems, Kim and Park (2009) have proposed the transport controlled MAC (TC-MAC). The listen periods are used for multi-hop channel reservation, reducing the end-to-end latency since packets will be forwarded as soon as they reach the next hop. Also, congestion is controlled through a backpressure mechanism, where a special message is sent locally to prevent close nodes from contending for the channel, and an explicit congestion notification with a traffic monitor that provides fairness. Their results have proven that energy consumption is reduced when compared to other cross-layer MAC proposals, reaching up to a reduction of 6 times the energy consumption achieved by IEEE 802.11.

Duty-cycles have been also considered in the cross-layer proposal by Misic et al. (2006a). First, a desired sensing reliability (number of packets per second for reliable event sensing at the sink) is set. Then, the proposed algorithms are responsible for duty-cycle scheduling in a multi-cluster WSN (Bluetooth scatternet) in order to avoid congestion and achieve the minimal sensing reliability. Their simulation results have shown that the reliability level is sustained, the packet loss ratio is decreased, sensors energy is saved, and congestion is reduced at the bridge nodes (responsible for inter-cluster communication).

Chehri et al. (2009) have studied the effects of rate and power allocation for sensor nodes on the same route. They have noticed that individually optimizing the routes, it becomes harder to meet end-to-end delay constraints. Thus, they have proposed a design capable of adapting its modulation scheme and transmission power in order to reduce the energy consumption of the nodes on the route. They have achieved up to 51% energy consumption reduction compared to the fixed rate and power scheme.

3.4. Physical layer

Ultra-wideband (UWB) is one of the technologies considered for the physical layer in cross-layer proposals for WSNs. This technology for short-range high-data rate transmission presents low complexity, low cost, and robustness against multipath fading and jamming (Chehri et al., 2009). Shi et al. (2006), Shi and Hou (2008), Chehri et al. (2009), and Melodia and Akyildiz (2010) have considered UWB in their optimization problems explained previously.

A cross-layer adaptive code position modulation (ACPM) scheme has been proposed by Yuan et al. (2005). The authors have defined a new layer—the packet scheduling layer, defined as a layer capable of calculating the delay and packet loss ratio requirements. From the delay requirement, the optimal modulation scheme can be chosen, and from the packet loss ratio, the physical layer can determine the maximum BER a packet may experience when transmitted. Thus, the transmission power for the decided modulation is adjusted in order to meet the requirements.

Sensors are small devices equipped with only one antenna for transmission and reception. However, MIMO communication, which requires a larger set of antennas per device, can be virtually achieved through the cooperation of nodes. This communication mode is also able to reduce energy consumption (Liang and Liang, 2009). Two cross-layer proposals have considered virtual MIMO communications—one by Liang and Liang (2009) and another by Yuan et al. (2006a). They have been commented previously in the *Network Layer* subsection.

Multilevel modulation has been considered in some cross-layer proposals. For instance, the previously discussed optimization framework proposed by Madan et al. (2006) considers a generic multilevel modulation with constellation size greater than or equal to four. Extending this proposal, Cui et al. (2007) have proposed another optimization framework, also discussed previously, but considering MQAM.

Tian and Ekici (2007) have proposed the multihop task mapping and scheduling (MTMS) in their work. This algorithm seeks the best application task mapping at each sensor node. Through dynamic voltage scaling (DVS), minimal power is used to schedule the tasks (and thus they take more time to be served), however respecting the delay constraints. Thus, nodes energy consumption is reduced by up to 52% when compared to the distributed computing architecture (DCA).

3.5. Multiple-layer standards

3.5.1. IEEE 802.15.4

The IEEE 802.15.4 standard (IEEE 802.15.4, 2003b) (IEEE 802.15.4, 2006) has been created for low-rate wireless personal area networks (Misic et al., 2006b), making it suitable for WSNs. It defines specifications for medium access control and physical layer. There are four possible transmission schemes. Three of them operate in the 868/915 MHz frequency range, one with direct sequence spread spectrum (DSSS) and binary phase-shift keying (BPSK) modulation, the other with DSSS and offset quadrature phase-shift keying (O-QPSK), and the last with parallel sequence spread spectrum (PSSS), BPSK and amplitude shift keying (ASK) modulations. The last scheme operates in the 2450 MHz frequency range with DSSS and O-QPSK modulation. Regarding the MAC layer, the two possible topologies rely on a PAN coordinator node to work, using CSMA/CA as medium access method. In peer-to-peer communication, nodes can communicate with others in range directly, but in star topology they need to communicate through the coordinator node (Misic et al., 2006b). Misic (2007) and Misic et al. (2006b) have considered this standard in their cross-layer proposals explained in a previous subsection.

3.5.2. IEEE 802.11

Also based on CSMA medium access method, the IEEE 802.11 (IEEE 802.11, 2007) defines 4 PHY schemes. The first operates in the 2.4 GHz frequency range using frequency hopping spread spectrum (FHSS). The second uses the same frequency range with DSSS. The third scheme uses communication through infrared (IR) with wavelengths from 850 to 950 nm. The fourth uses orthogonal frequency division multiplexing at the 5 GHz band. Also, there are two data rate extensions defined in the standard. At the MAC layer, it uses request to send (RTS) and clear to send (CTS) frames to contend for the medium (when operating in distributed coordination function—DCF-mode). This is suitable for large networks, but it wastes more energy on idle listening when traffic is light (Kim and Park, 2009). Thus, Kim and Park (2009) have proposed an extension to the IEEE 802.11 MAC to avoid this waste of energy. This is carried out by the assignment of listen periods and changing nodes to *sleep* mode when they are not supposed to listen, as explained previously.

3.5.3. IEEE 802.15.3

The IEEE 802.15.3 standard was proposed for high-rate applications in wireless personal area networks (WPANs) (IEEE 802.15.3, 2003a), which is suitable for video and audio transmission on WSNs. It specifies the operation of WPANs at the 2.4 GHz with QPSK, differential quadrature phase-shift keying (DQPSK), 16-quadrature amplitude modulation (QAM), 32-QAM, and 64-QAM. The MAC specification defines the use of a hybrid CSMA/CA and TDMA. Chen et al. (2006b) have considered a modification of these medium access methods, the pseudo-static TDMA (pTDMA). This medium access method prevents collisions since it is contention-free, nevertheless it affects fairness since transmitting nodes and idle nodes have transmission time allocated to them equally. Thus, Chen et al. (2006b) have proposed a cross-layer solution for this problem, assigning QoS priorities to the different data flows and providing medium access based on the defined priorities. More details on this solution have been given in a previous subsection.

3.5.4. Bluetooth

Bluetooth has also been considered for WSNs. This technology uses frequency hopping spread spectrum technique, reducing the interference from other networks operating at the same frequency. It can achieve up to 3 Mbps and up to 100 m of transmission range, making Bluetooth suitable for medium-rate WPANs. Also, this technology organizes networks in piconets (clusters with up to seven active devices and one piconet master), and medium access is done by TDMA/time-division duplex (TDD) (Misic et al., 2006a). As with IEEE 802.15.3, collisions are prevented, but energy can be saved if nodes go to *sleep* state when other nodes are assigned to transmit. However, event reliability, measured as the number of packets per second for reliable event detection at the sink node, is a requirement that conflicts with nodes *sleep* duration, and thus a tradeoff must be sustained. In order to study these effects of reliability, Misic et al. (2006a) have proposed a study for Bluetooth WSNs, explained previously.

4. Open issues

It is possible to infer that QoS and energy saving are the most important aspects of video transmission over WSNs. Furthermore, it can be seen that regular routing can quickly deplete sensors energy in the video stream path. Thus, it is clear that QoS provisioning, routing, and energy consumption are tightly connected. Video transmission still has to be further investigated in order to create optimal energy-efficient and QoS-aware routing protocols suitable not only for IEEE 802.15.3, but also for other technologies. Furthermore, only VBR video and FEC techniques have been tested so far, and even though it is known that ARQ can be harmful for QoS delay requirements, it is worth to run some tests on video transmission over WSNs to analyze its effects. Moreover, DSC has been tested only without considering real data transmission. It would be interesting to combine the transmission of video and DSC to test if data can be decoded at the sink node while saving energy by reducing the number of bits transmitted. This solution would probably require advanced video processing/coding techniques. Also, it is clear that data fusion cannot be combined with video transmission since each sensor will gather different data. However, data fusion algorithms could benefit from routing protocols by forwarding the measured data to the nearest common node. Then, the fusion could be carried out, avoiding the transmission of several measurements data to a sink node, and thus reducing energy consumption. Finally, it can be seen that only a few proposals involving the application layer have been actually deployed. There is still much room for improvements solving the problems that arise during the deployment of cross-layer proposals.

Furthermore, it can be concluded that new routing protocols are difficult to be created. All aforementioned solutions involving routing protocols are extensions of other previous protocols. Thus, other known routing protocols can become part of cross-layer bandwidth-aware optimizations, creating the opportunity for many contributions. Moreover, the commonly used metrics for routing (*e.g.*, shortest path) can be replaced by others that include energy consumption, interference and/or channel state. Virtual MIMO communication can affect routing since it can make farther nodes become neighbor ones. Thus, the combination of virtual MIMO and routing protocols must be further investigated to verify its advantages and drawbacks. Also, none of the cross-layer solutions has been deployed on testbeds. Comparisons between the simulated or calculated WSN performances and results achieved in testbeds can be a source for further routing protocol development. Also, the most efficient routing hierarchy has not been identified. Some solutions suppose it is the clustered hierarchy, others use single-hop approaches, and also flat hierarchies can be found. Thus, each hierarchy considered needs to be assessed in terms of the network objective in order to identify which one results in higher throughput, less end-to-end delay, and so on.

From the presented proposals, it is clear that the most used medium access control methods are CSMA and TDMA. However, these access methods are considered in different scenarios, assuming the chosen one will perform better for the considered WSN. Literature lacks of a comparison of these most used MAC protocols. Also, the scheduling of *sleep*, listen and transmit times has showed to be of great importance to save sensors energy. Nevertheless, it can also severely interfere on QoS constraints. Thus, these schedules must be carefully studied in each scenario, and then a general rule should be proposed. Furthermore, the use of CSI helps to avoid wasting network resources. Medium access is scheduled to the sensors experiencing a good channel state (opportunistic scheduling), however this can lead to unfairness. Thus, mechanisms that make use of CSI must also include methods to improve scheduling fairness. Moreover, CSI can be used to change modulation schemes and for transmission power control. Modulation schemes have different error resiliencies, thus more robust schemes can be used when a sensor experiences a bad channel, and also transmission power can be increased to reach other nodes with more reliability. However, more interference can reduce links capacity and increase packets error probability. Hence, the tradeoff between self-benefit and network benefit must be analyzed when changes in modulation and power control are used.

It is also possible infer that UWB is a promising technology for WSNs due to its high achievable transmission rate and its robustness. Moreover, it can be combined to CSI and REI, as discussed in previous subsections, to improve energy efficiency. Virtual MIMO has been considered as well, and this technique has proven to save energy by the exploitation of nodes cooperation. It could also be achieved by regular MIMO techniques, but sensor nodes are power- and size-constrained, and thus placing more antennas on sensor nodes becomes infeasible. Furthermore, multilevel modulation enables sensors to adapt to the channel quality dynamically, also leading to energy saving. Moreover, DVS has been used to save sensors energy by reducing data processing energy consumption, when QoS constraints allow a small increase in processing delays. Finally, we are able to conclude that physical layer considerations are the key for energy consumption reduction. Thus, all sensors physical capabilities available (virtual MIMO, CSI, REI, multilevel modulation, and DVS) must be exploited in order to reach optimal network energy consumption in real networks.

Scenarios considered in the solutions comprise different numbers of sensors in the WSN. It is clear that scalability can severely affect the operation of routing protocols, also leading to congestion. Little work has been done on the limits of proposals operation. It is also worth noting that scalability is different depending on the considered scenario. For body area networks, a scalable solution might be able to comprise up to 20 sensors, while in a disaster area monitoring solution, up to many hundreds of sensors might be necessary. Thus, the operation boundaries of the solutions should be assessed, and they must cope with the considered application scenario.

Furthermore, only a few proposals consider sensors mobility. It has been argued that the proposal of new routing protocols is not an easy task, and by considering mobility more complexity is expected. While low mobility is experimented by tracked assets in a warehouse, a vehicular traffic sensoring solution needs to cope with high mobility. This is certainly one of the larger challenges cross-layer research will have to deal with.

One of the disadvantages of cross-layer design is its lack of interoperability with protocols running on commercial solutions. A few solutions have considered interoperating with existing systems, and thus it can be seen that this will remain an open issue for some time, specially because new protocols are frequently proposed without regarding interoperation. More efforts should be directed towards the creation of architectures, or a single architecture, that can interoperate with the existing protocol stack. After this definition, protocols could be proposed following its rules, guaranteeing that different cross-layer solutions could coexist in systems operating with non-cross-layer applications. Moreover, as shown by cross-layer optimization framework proposals, the more layers are considered, the better the optimization approach. Thus, it can be inferred that by considering all the layers should result in the best cross-layer solutions. However, the complexity of the solutions also increase with the number of layers considered. Hence, the proposed architecture must handle all the layers. Another assumption made by optimization proposals is that parameters of the whole network are accessible by the optimizer. In practice, this would increase the control transmission, yielding overheads. On the other hand, distributed solutions cannot achieve optimal parameters selection. Thus, the tradeoff between overheads and the optimality of the solution needs to be studied, and if an interoperable architecture is to be proposed, it must also cope with parameters exchange between sensor nodes.

5. Conclusions

The great number of cross-layer approaches that address the challenges presented by the new applications of WSNs proves that there is still need for further optimization of these networks, and that cross-layering is efficient to accomplish that. Thus, in this survey most of the recent research on this field has been gathered and discussed. Proposals have shown that there are different categories of WSNs, and that each of them has their own set of problems to be addressed. Furthermore, well-known problems have been discussed and some available cross-layer solutions have been briefly presented. Then, the layers and used technologies have been discussed, also presenting cross-layer approaches that are examples of the used technologies. Moreover, open issues have been identified through the insights provided when the approaches were gathered. At the application layer, QoS provisioning is the main challenge. For the MAC layer, duty-cycles scheduling has proven to save energy with different designs for each medium access method. And at the physical layer, some effects of the use of multilevel modulation and the consideration of parameters measured at this layer, *e.g.*, CSI and REI, by other layers has been shown. Furthermore, some of the standards considered in cross-layer approaches have also been presented.

Some directions for future research are given next. From the application layer, it has been seen that strict QoS parameters may need to be respected depending on the running application. However, as it can be counterproductive for the WSN lifetime, further investigation needs to be carried out to verify the behavior of the used multimedia coder (MPEG, H.263, H.264) on the sensors energy consumption. Generally, the work that considers these QoS requirements and coders only consider packet error rates at the physical level. Thus, as more complex channel models are available in research work that does not consider the application layer, these proposals could be combined to result in a more detailed design that considers the effects of the physical characteristics on the application. Also, none of the discussed work involving the application layer has been deployed, and thus only analytical and simulation results are available. This is an interesting challenge to be addressed in the future. Moreover, routing comprises the most challenging set of issues on WSNs. There is no consensus on the best approach for routing since some proposals consider clustered networks, others consider flat routing (no hierarchy), and also some consider centralized routing. The number of sensors in the WSN can clearly affect the performance of each approach, requiring scalability tests that have not been done in the literature. Furthermore, sensors mobility are rarely considered. The high complexity of the proposed routing protocols for WSNs is increased by considering mobility, demanding a great amount of effort from researchers to fill this gap. Also concerning the network layer, MIMO effects on routing protocols have been only superficially verified, and spatial diversity has not been explored yet. Besides, cross-layer proposals do not agree on the most efficient medium access method for WSNs. Several MAC protocols have been created based on TDMA and CSMA, but the literature lacks of the comparison between them. In addition, boundaries between uplink and downlink phases, optimal frame sizes, and synchronization methods are still open issues. Finally, to properly address the efficiency of the different modulation and transmission technologies considered in cross-layer design, an extensive comparison between them is needed. Clearly, as they are closely related to the channel properties and energy consumption profile, they directly affect the parameters at the upper layers. Hence, there is still much to be done in order to achieve a comprehensive cross-layer design that addresses the issues at every layer of the stack in an energy-efficient manner, but also considering the application requirements.

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