Physical Layer and Medium Access Control Design in Energy Efficient Sensor Networks: An Overview

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***Abstract*—It is now well expected that low-power sensor networks will soon be deployed for a wide variety of applications. These networks could potentially have millions of nodes spread in complex indoor/outdoor environments. One of the major deployment challenges under such diverse communication environments is providing reliable communication links to those low cost and/or battery-powered sensor nodes. Over the past few years, research in physical (PHY)-layer has demonstrated promising progresses on link reliability and energy efficiency. In modern medium access control (MAC) design, energy efficiency has become one of the key requirements and is still a hot research topic. In this overview, we provide a broad view encompassing both PHY- and MAC-layer techniques in the field of sensor networks with a focus on link reliability and energy efficiency. We review work in systems employing various PHY techniques in spatial diversity, energy efficient modulation, packet recovery, and data fusion, as well as MAC protocols in contention-based duty cycling, contention-free duty cycling, and hybrid duty cycling. The latest developments in cross-layer MAC designs that leverage PHY-layer techniques are presented. We also provide a synopsis of recent development and evolution of sensor network applications in industrial communications.**

***Index Terms*—Cross Layer, energy efficient sensor network, medium access control (MAC) layer, physical (PHY) layer, sensor network standards.**

I. INTRODUCTION

THERE HAS been a significant amount of research that makes smart environment technologies, which rely on real-time sensor measurements of real-world phenomena, a reality. Past improvements in medium access control (MAC)-layer and physical (PHY)-layer techniques have led to the current sensor network deployment.

Nowadays, advanced sensor networks are actively being developed and will support a large number of low-cost sensor nodes spread over a wide area. These advanced sensor network technologies have the potential to revolutionize various applications in smart grid, large-scale monitoring, and industrial control and automation.

In sensor networks, a general application is to utilize all sensor observations available in the entire network to perform certain tasks, such as estimation of parameters or signals. Suppose, for instance, a scenario where there are four clusters of distributed sensors in the network in Fig. 1. Each sensor in a cluster attempts to deliver a local observation to the fusion center. The fusion centers extract parameters or signals from the collected sensor observations.

MAC protocols, in general, concern medium allocation and scheduling among the fusion center and sensor nodes. PHY-layer, on the other hand, provides the actual mechanism for sensor data transmission and reception. To fulfill different application objectives, a large number of MAC- and PHY-layers technologies have been developed for sensor networks.

In modern sensor networks, enhancing energy efficiency has become a key design criterion. In particular, communication energy efficiency for battery-powered sensor nodes is essential because sensor node transceivers consume a major portion of battery energy and it is costly/impractical to replace the batteries of a large number of sensor nodes. This criterion also applies to sensors connected to power lines. Because utilities have to provide electric power to millions of sensors, consuming low power is essential to their operation.

Efficient MAC protocols for sensor networks must minimize the energy consumption under dynamic network traffic and topology, while still meeting the constraints on latency, throughput, and quality of service (QoS) (e.g., see the discussion in [1] and [2] and the references therein). Initial work in PHY-layer for distributed sensor communications would trace back to techniques utilizing spatial diversity [3], distributed synchronization [4], and distributed sensor data fusion [5].

Based on the initial work in MAC- and PHY-layer, significant progresses that enhance both the link reliability and energy efficiency have been reported during past few years, separately in MAC- and PHY-layer. Interest has continued to grow in cross-layer techniques.

In this paper, we present an overview of the latest research in both sensor network MAC and PHY. The aim is to investigate the latest development in both industry and academia and to provide directions for future research. The uniqueness of MAC- and PHY-layer review presented in this overview is to focus on how the state-of-the-art MAC- and PHY-layer techniques in sensor networks have evolved and how the MAC techniques have been taking recent features from the PHY-layer to further increase efficiency. The PHY review focuses on reliable and energy efficient transceiver designs. Thus far, we are not

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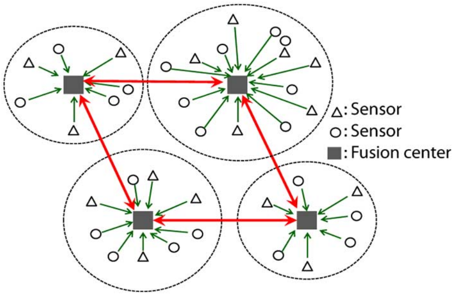

Fig. 1. Representation of sensor networks with four clusters.

aware of previous review work that encompasses both MAC- and PHY-layer techniques for modern sensor network design.

We first summarize reliable and low-energy PHY techniques in Section II. We divide the MAC section (Section III) into two main areas: 1) recently developed energy efficient MAC protocols; and 2) cross-layer techniques. The relation between techniques in Sections II and III and recent cross-layer designs are illustrated in Fig. 2. Emerging sensor network communication standards for industrial applications are presented in Section IV. We provide some suggested research directions and concluding remarks in Sections V and VI, respectively.

II. RELIABLE AND LOW-ENERGY PHY TECHNIQUES

The PHY techniques for low-power sensor nodes largely focus on how to attain diversity gains (i.e., reliability benefits) and lower the computational overhead. We address the impact and the role of these techniques with an emphasis on energy efficiency.

The PHY-layer, in general, involves two main tasks: 1) the design of energy efficient and reliable transmission and reception; and 2) the design of low complexity sensor data fusion rules to fulfill application objectives such as event detection, decision making, and target tracking. Even though we focus on wireless sensor technologies in this section (except for Section II-B), these technologies can be generally adopted to wired applications (e.g., Section IV-A).

A. Energy Efficient and Reliable Transceiver Design

Low-cost and low-powered sensors suffer from high failure rate. This is because batteries are not only energy limited but also peak-power limited. This limitation makes sensor nodes infeasible to be deployed for many practical scenarios. Hence, not only energy efficient but also reliable transmission techniques become crucial.

1) Spatial Diversity Techniques: Traditionally, reliable communications in PHY have been achieved by exploiting different forms of diversity gains. The most suitable gain that the spatially distributed sensors can harness is the spatial diversity gain and this is typically attained by either employing space-time block code (STBC) or using beamforming.

Both the STBC and beamforming techniques utilize spaced multiple antennas and design signals to achieve the diversity benefit and/or signal-to-noise-ratio (SNR) gain. The key difference between these two techniques is that beamforming, in general, requires channel state information (CSI) at the transmitter, while the STBC does not necessarily rely on CSI at the transmitter.

Since CSI is utilized, the fundamental channel capacity of beamforming is larger than that of the STBC. We will briefly review these two key techniques. This overview will be found useful in the later part of this section.

a) STBC: The Alamouti type [6] is the most popular and practical STBC scheme. The transmitter is equipped with two transmit antennas and the receiver has one receive antenna.

We denote the channel coefficient from ith transmit antenna to the receive antenna as $h_i \in \mathbb{C}$. The transmitter sends two symbols $s_1, s_2 \in \mathbb{C}$ during two channel uses. At the first channel use, the first antenna sends symbol s_1 and the second antenna sends symbol s_2, concurrently. Then, the received signal is $y_1 = h_1 s_1 + h_2 s_2 + z_1$, where $z_i \in \mathbb{C}$ is the complex Gaussian noise. In the second time instance, two antennas change the symbols with conjugate and negate the symbol at the second antenna, resulting in the received signal, $y_2 = h_1 s_2^* - h_2 s_1^* + z_2$.

Manipulating the received signal in a space–time format yields $[y_1\ y_2^*]^T = \mathbf{H}[s_1\ s_2]^T + [z_1\ z_2^*]^T$, where $\mathbf{H} = [\boldsymbol{h}_1\ \boldsymbol{h}_2]$, $\boldsymbol{h}_1 = [h_1 - h_2^*]^T$, $\mathbf{h}_2 = [h_2\ h_1^*]^T$. Notice that the effective channel $\mathbf{H}$ satisfies $\mathbf{H}^*\mathbf{H} = (|h_1|^2 + |h_2|^2)\mathbf{I}_2$ with $\mathbf{I}_2$ being the 2×2 identity matrix and $\mathbf{H}^*$ being the conjugate transpose of $\mathbf{H}$. Multiplying $\mathbf{H}^*$ to the received $[y_1\ y_2^*]^T$ yields $[\tilde{y}_1\ \ \tilde{y}_2^*]^T = (|h_1|^2 + |h_2|^2)[s_1\ \ s_2]^T + \mathbf{H}^*[z_1\ \ z_2^*]^T$, where $[\tilde{y}_1\ \tilde{y}_2^*]^T = \mathbf{H}^*[y_1\ y_2^*]^T$.

The Alamouti scheme supplies the receiver with two independently faded replicas of the same information symbol (e.g., $\tilde{y}_1$ contains two replicas $|h_1|^2 s_1$ and $|h_2|^2 s_1$). In this case, the probability that all the signals fade simultaneously is reduced by a factor of 2, and the Alamouti STBC achieves a spatial diversity gain of 2, which is the maximum that a two antenna system can achieve. Furthermore, the Alamouti technique facilitates a simple decoding procedure. The reliable and low complexity operations make this technique utilized by low-power sensor nodes (see the discussion in Section II-A2a).

b) Beamforming: Beamforming is a technique to send multiple coherent replicas of a symbol through multiple antennas. For multiple-input single-output (MISO) systems with M transmit antennas and a single receive antenna, the channel input and output relation can be modeled via $y_1 = \boldsymbol{h}^* \boldsymbol{f} s_1 + z_1$, where $\boldsymbol{h} = [h_1, \ldots, h_M]^T \in \mathbb{C}^M$ denotes the channel vector and $\boldsymbol{f} \in \mathbb{C}^M$ represents the beamforming vector, $||\boldsymbol{f}||_2 = 1$, where $||\cdot||_2$ denotes the vector 2-norm. To provide nontrivial gain, the $\boldsymbol{f}$ must be designed as a function of the CSI $\boldsymbol{h}$.

A practically well-motivated beamforming technique is the equal gain transmission [7], which co-phases the signals transmitted from different antennas. In this approach, each beamforming weight f_i is constrained $|f_i|^2 = \frac{1}{M}$. It can offer both diversity gain (i.e., spatial diversity order M) and SNR (i.e., beamforming) gain. Though the equal gain transmission is suboptimal,[1] it offers cheap transmitter (only phase shifters are implemented) and reduces CSI requirement (only phase information is used) at the transmitter. Due to these cost-efficiency and low overhead benefits, interest has grown to employ this technique to sensor nodes (see Section II-A2b).

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[1] It is suboptimal in the sense that it does not provide the maximum achievable SNR. For the max SNR beamforming, see the discussion in [7].

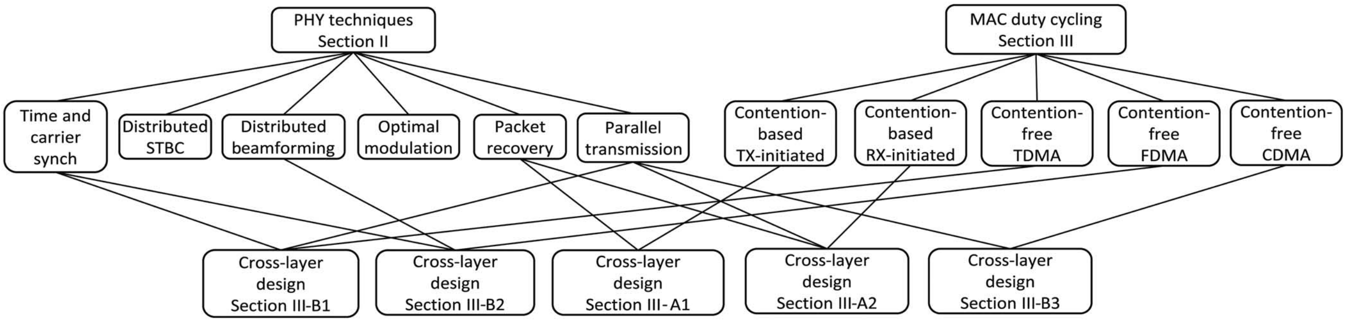

Fig. 2. Tree diagram showing the connection among PHY, MAC, and cross-layer techniques treated in Sections II and III.

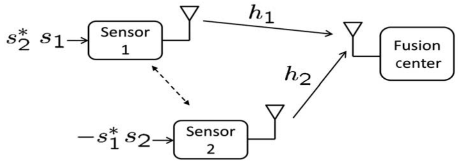

Fig. 3. Distributed Alamouti STBC system.

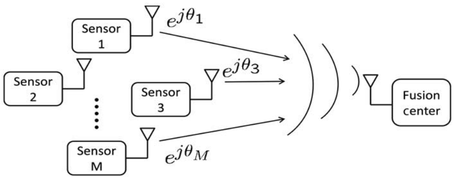

Fig. 4. Distributed beamforming system.

2) Energy Efficient Diversity Techniques for Distributed Sensors: Transceivers with multiple antennas are luxury and consume significant power. Hence, they are unlikely to be employed by cheap sensor nodes. Much of work in sensor networks, alternatively, treats spatially distributed single antenna sensor nodes as a distributed antenna system and adopts the STBC and/or beamforming techniques, namely distributed STBC and distributed beamforming techniques.

In the distributed STBC or beamforming, attaining global synchronization is very important. The synchronization involves carrier synchronization and time synchronization. Precise time synchronization algorithms (e.g., techniques in [4]) can be used for great precision. The carrier synchronization is further divided into carrier frequency synchronization and phase synchronization. Various practical algorithms for carrier frequency synchronization {e.g., master-slave (MS) architectures in [8]} are available. The phase synchronization impacts the performance of distributed beamforming. Since STBC does not utilize CSI at the transmitter, it is relatively robust to the phase offset.

The time and/or phase synchronization, in practice, however consumes large amount of energy. Thus, much of work focuses on the schemes that reduce the energy consumption for gaining time and phase synchronization.

a) Distributed STBC: Suppose that two sensors with one antenna, in Fig. 3, collaborate to emulate the Alamouti STBC system, for which a tight time synchronization between two nodes is required. To relieve the tight synchronization burden, time reversed distributed Alamouti STBC is proposed in [3]. The time reversal operation effectively equalizes the relative time difference between two nodes. However, it relies on coherent detection, and must estimate and compensate the delay of two multiplexed signals. Attaining precise common delay estimates is still demanding especially when multiple nodes transmit simultaneously.

Alternatively, the energy efficiency of distributed Alamouti STBC in the presence of synchronization error and training overhead is investigated in [9]. It is reported that the degradation is somewhat negligible if the time offset is within an acceptable margin. Though the work [10] ignores the impact of the synchronization error, it analytically formulates the energy efficiency of the distributed STBC in terms of the transmission range and different modulation schemes. Transmission energy increases with transmission distance d and it is the dominating factor of the total energy consumption for long range transmission [9], [10].

Applying free-space pathloss model, we have $P_t \propto P_r(4\pi d f_c)^2$, where P_t is the transmit power, P_r is the required received power for link margin, d is the distance, and f_c is the operating frequency [11]. This is, to say, in order to meet the required receive power, the transmit power has to quadratically increase as d grows.

For example, the transmission energy consumption typically starts to overwhelm the circuit energy consumption when $d \geq 10$ m for a single antenna system operating at $f_c = 2.5$ GHz with the bandwidth 10 kHz [10].[2] Hence, depending on the applications and size of the network, providing SNR improvement (thus increasing the transmission range) without increasing the transmission energy is often a more important design criterion for reliable sensor access, motivating the beamforming.

b) Distributed Beamforming: In distributed beamforming, sensor nodes sharing a common message in a cluster emulate a centralized antenna array to implement the equal gain transmission [7] so that their phases are added constructively at the receiver (see Fig. 4). Realizing this technique requires both perfect synchronization and accurate CSI at each node to correctly adjust the antenna phase.

Assuming perfect CSI and the synchronized nodes, various energy efficient distributed beamforming schemes are reported [10], [12]. The power control that prolongs the

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[2] Another important aspect to note is that one of the advantages using lower frequency band is that the transmit power is decreased proportional to f_c^2 (e.g., sub-1-GHz radios for 802.15.4-based protocols in Section IV).

lifetime of a sensor cluster is proposed in [12]. The overhead in sharing information among clustering sensor nodes is taken into account for energy analysis in [10]. The work [10], [12], however, impractically assumes perfect CSI and/or synchronization.

In the presence of imperfect synchronization, an important feasibility study of distributed beamforming is reported in [8]. In this study, it is verified that a large fraction of the beamforming gain can still be achieved even with imperfect synchronization with acceptable variance.

In practice, it is desired to have a low rate feedback link from the receiver to the multiple sensor nodes to provide partial CSI so that the sensor nodes leverage this information to attain some coherence among other nodes.

In [13], an energy efficient 1-bit feedback scheme is proposed. This feedback tells nodes whether currently picked phases are good or not. If the feedback is "good," the nodes keep current phase and otherwise, the node makes a random adjustment to the previous value. This distributed ascent algorithm [13] is shown to achieve almost sure phase coherence.

A variation of the 1-bit feedback which adaptively adjusts the phase shift according to time-varying channel statistics has also been proposed [14]. In [15], non-one bit feedback algorithm that selects the optimum phase offset by solving a numerical equation is proposed.

Arguably, closed-loop distributed beamforming, that utilizes low overhead feedback link, is one of the most practical ways to realize coherent beamforming. However, feeding back some information comes at the price of nonnegligible energy consumption. In [16], it is separately reported that incorporating robust error correction code and multiplying the transmitted signals with random phases can still improve the beamforming gain without CSI feedback.

3) Energy Constrained Modulation and Packet Recovery: The distributed beamforming is a robust method for long distance communications. For short distance transmission (e.g., $d \leq 10$ m with $f_c = 2.5$ GHz and bandwidth 10 kHz [17]), the circuit energy consumption dominates the transmission energy [17]. In this case, it is desired to optimize modulation sizes and/or transmission durations (i.e., link adaptation) to minimize the energy consumption of the sensor nodes.

Provided M-ary ($M = 2^b$ with b being the number of bits per symbol) modulation schemes, the problem of designing the optimal modulation size (i.e., the optimal b_{opt}) that minimizes the total energy consumption subject to the delay and peak power constraints is first considered in [17]. Unlike [17] that focuses on Gaussian channels, the modulation optimization for a fading channel subject to the bit-error-rate (BER) constraints with various transmission scenarios (e.g., multihop, path loss, and retransmissions) is investigated in [18].

Interestingly, there exists a threshold for the transmission distance d above which no energy saving is possible by optimizing the modulation, which then should just be set to the maximum transmission duration with the lowest modulation class [17], [18]. For instance, the optimal modulation size decreases as d grows and it converges to $b_{\mathrm{opt}} = 2$ when $d \geq 30$ m for a single antenna system operating at $f_c = 2.5$ GHz with the bandwidth 10 kHz [17].

While low-energy transmission is important, tight energy margin would cause high symbol error rate (SER). In packet mode transmission, a collision also occurs when multiple nodes transmit simultaneously. In the case of symbol error or collision, the receiver requests retransmission, which, in turn, significantly increases energy consumption for the network to perform control operations.

Robust transmission schemes that jointly adapt packet retransmission mechanism and forward error correction [19] or modulation scheme [18] are proposed. An alternative scheme directly optimizing the target SER to minimize the energy consumption is proposed [20]. Recently, a scheme combining a nonbinary turbo code and network coding is proposed [21].

Packets involved in a collision are usually assumed undecodable and discarded. In practice, it is possible to recover some or all packets from a collision, without retransmission. This phenomenon is captured by the packet recovery mechanisms [22]–[24]. Energy efficient outer erasure-coding schemes show a higher tolerance to packet losses than packet retransmission when compared in a lower energy consumption setting [22], [23]. Single-user detection, the so-called power capture, detects its own signal by treating the others as noise [24], when collision occurs. The received signal can be successfully recovered as long as the signal to interference-plus-noise ratio (SINR) exceeds a certain threshold. However, the power capture only allows one signal recovery [24].

Detection of multiple collided signal is also possible by using multiuser detection techniques [25]–[28]. Multiuser detection techniques can be used to resolve multiple collided control signals from simultaneous sensors [26]–[28]. These techniques can lower the latency in delivering important control data from a large number of sensors to the receiver. To correctly resolve the multiplexed signals, signal orthogonality in frequency domain [26], or signature domain [27], [28] is necessary. Simple energy detection techniques are employed in [26]–[28].

As will be seen in Section III-B1, time division multiple access (TDMA) MAC leverages these techniques to alleviate the sensor scheduling overhead. Various aspects of the implementation of parallel transmission using OFDM PHY specifications [29] have been studied [27] and high-energy efficiency is verified through the field programmable gate arrays (FPGA) prototype [26].

B. Low Complexity Sensor Data Fusion

After reliable reception of sensor observations, the fusion center (see Fig. 1) must extract common network-wide parameters or signals from the gathered observations, called *sensor data fusion*. Early studies in sensor data fusion trace back to the work by [5]. The goal is to reduce the network overhead while satisfying required sensor data estimation performance. All nodes contribute to the estimation of a global variable, $\boldsymbol{\theta} \in \mathbb{C}^{p\times 1}$, which is commonly observed by all nodes.

There are N spatially distributed sensors as shown in Fig. 5 and we denote a noisy observation of $\boldsymbol{\theta}$ as $\boldsymbol{x}_n = \boldsymbol{\theta} + \boldsymbol{z}_n$, $n = 1, \ldots, N$ with $\boldsymbol{z}_n \in \mathbb{C}^{p\times 1}$ being the additive noise.

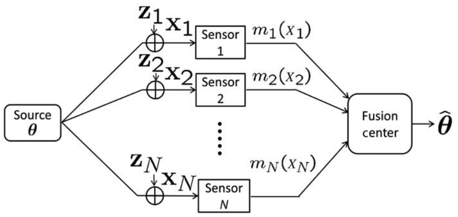

Fig. 5. Each sensor makes a noisy observation of the source $\boldsymbol{\theta}$, compute a local message, and transfers it to the fusion center.

The additive Gaussian noise channel is commonly assumed in the low complexity data fusion techniques, e.g., [5], [30]–[38].

Delivering raw data $\mathbf{x}_n$ from a sensor to the fusion center requires infinite bandwidth. In order to meet the bandwidth requirement, each sensor computes a local message $m_n(\mathbf{x}_n)$, $n=1,\ldots,N$, where $m_n(\cdot)$ can be either a vector quantizer or a linear compression function. Then, all the computed local messages are transmitted to the fusion center. They are combined at the fusion center to produce an estimate of $\boldsymbol{\theta}$.

1) Distributed Quantized Estimation: The distributed quantized estimator can be designed by minimizing mean-square-error (MSE) [30], [31] or by maximizing likelihood (ML) [32]–[34] between $\boldsymbol{\theta}$ and $\hat{\boldsymbol{\theta}}$.

The distributed quantized estimator for MSE minimization problem is first reported in [30] where the optimal quantization bit lengths are designed to be proportional to the logarithm of the local SNR. The size of quantization bits has a direct impact on energy efficiency. As the operating SNR increases, the size of the quantizer must grow [$N \propto \log(\mathrm{SNR})$] [30], resulting in higher energy consumption.

Naturally, observations from sensors, sharing the same source, are spatially correlated. Utilizing the correlation statistics for the quantized estimate design makes energy consumption of sensors minimized, while achieving the target MSE requirement [31].

Another form of distributed quantized estimation can be designed by maximizing likelihood (ML). The quantized-estimator design that minimizes the worst case Cramer–Rao lower bound (CRLB) has been studied [32]. The threshold-based quantization is not suitable for high-SNR situations because the max CRLB increases exponentially at high SNR.

This problem is resolved by dithering the observation prior to threshold quantization [33]. Feedback from the fusion center can have immediate impact in enhancing estimation performance. An adaptive quantization approach where the fusion center feeds back the mean and variance of the receive signals is proposed [34] and verified that feedback facilitates energy-efficient node transmissions.

2) Distributed Compressed Estimation: Dimension reduction of local data at the sensor nodes is an efficient approach to reduce the energy consumption. The problem of interest is to jointly design the linear compression functions to minimize the estimation error at the fusion center.

Kalman filer-like approach [39] is proposed to characterize the minimum compressed signal dimension subject to a loss of estimation performance. A distributed Karhunen–Loeve (KL) transform [35] is proposed to characterize the optimal dimension reduction. In [39], the communications links are assumed perfect. This assumption is relaxed in [36] where the measurement noise and transmit power constraints are taken into account in designing the compression matrices. The joint dimension allocation and suppression matrix optimization has been studied in [37].

The compressed estimation, in general, relies on iterative techniques to design the compression filters. The algorithm convergence depends on the forward/backward iteration and channel noise, resulting in potentially large energy consumption.

Unlike above mentioned approaches, a more general distributed estimation problem where each node observes a different node-specific signal $\boldsymbol{\theta}_n$ is recently investigated in [38]. The approaches in [38] verify that if the node-specific signals share a common unknown signal subspace, estimation using reduced dimensionality can reduce the total energy consumption.

Table I recapitulates the key energy efficient distributed diversity, optimal modulation, packet recovery, and fusion techniques discussed in this section.

The common assumption of the PHY techniques discussed in this section is the existence of secured medium between the transmitter and receiver. MAC protocols are concerned with resolving the reliable medium/channel and scheduling the medium access. Judiciously designed MAC protocols, on top of the reliable PHY techniques, could significantly enhance energy efficiency and most of the meaningful energy savings could be achieved by adopting smart MAC strategies.

III. ENERGY EFFICIENT MAC PROTOCOLS

MAC protocols for sensor networks have been extensively studied in the literature. A large number of reviews, e.g., [1], [2], on this subject can be found in the literature. In this overview, instead of focusing on the MAC protocol alone, we take a different approach by putting emphasis on cross-layer design. We review how the state-of-the-art MAC protocols have been benefited from the PHY-layer to increase efficiency.

Idle listening is one of the most significant sources of energy consumption in battery-powered sensor nodes. In idle listening, a node listens for any possible incoming packets. The large power consumption comes from two sources. First, the entire radio-frequency (RF) chain needs to be powered on to receive signals. Second, the micro-processor that drives the MAC layer also needs to be active. For low-cost radios used in wireless sensor networks, MAC processing is typically offloaded to the host processor, and is a significant source of power drain. For example, Intel-5300 WiFi NIC (Network Interface Card) operating under 802.11n mode draws 802 mW in idle listening state [40].

Many solutions to this idle listening problem are based on the technique of duty cycling [41], [42]. In this technique, each sensor node has its radio-active only periodically, alternating between active and sleeping states. If the node is inactive, the node completely turns off its radio to save energy. Duty-cycling MAC protocols in the literature can be roughly categorized into

TABLE I
MAJOR DISTRIBUTED PHY TECHNIQUES FOR SENSOR DATA TRANSMISSION AND FUSION

Major PHY techniques	Channel	Methodology and design criterion
Distributed STBC [3], [10]	Fading	Minimize energy consumption by optimizing modulation or providing self-time synch
Distributed BF [8], [12]–[14], [16]	Fading	Reduce energy consumption in carrier synch using power control, feedback, and MS architecture
Optimal modulation [17], [18]	Fading	Minimize energy consumption under delay, peak power, and BER constraints
Packet recovery [20]–[23]	Fading	Reduce energy consumption in retransmission under SER constraint or using efficient coding
Parallel transmission [26], [27]	Fading	Reduce latency in delivering multiple control data
Distributed quantizer [30]–[32], [34]	AWGN	Minimize energy consumption under MSE and ML criteria using correlation, dithering, feedback
Distributed compression [36], [38], [39]	AWGN	Optimize compression matrices under target performance constraint

Fig. 6. Operation of X-MAC with the strobed preamble.

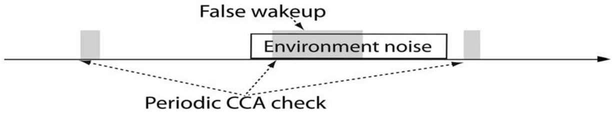

Fig. 7. False wakeups triggered by environmental noise.

contention-based and contention-free approaches, together with some hybrid approaches.

A. Contention-Based Duty-Cycle MAC Protocols

In the contention-based approach, some mechanism is needed in order for the sender and receiver to "rendezvous" in time. Based on how the rendezvous time is achieved, we categorize existing work into transmitter-initiated protocols and receiver-initiated protocols.

1) Transmitter-Initiated Duty-Cycle MAC Protocols: B-MAC [42] and X-MAC [43] are representative transmitter-initiated duty-cycle protocols. In particular, in B-MAC, each node periodically wakes up to check if there is any activity on the wireless channel. Prior to DATA frame transmission, a sender transmits a long "wakeup signal," called a preamble, which lasts longer than the receiver's sleep interval. This policy ensures that the receiver will wake up at least once during the preamble.

B-MAC is very energy efficient under light traffic. However, a node with B-MAC may wake up and remain awake due to channel activity, only to, in the end, receive some DATA frames actually destined for other nodes.

X-MAC solves this overhearing problem by using a strobed preamble that consists of sequence of short preambles prior to DATA transmission, as illustrated in Fig. 6. In this and similar figures in this paper, the period of time during which a node is active is indicated by a solid gray background, frame reception by a node is indicated by black text on the gray background, and frame transmission by a node is indicated by white text on a dark background.

In Fig. 6, the target address is embedded in each short preamble, which not only helps irrelevant nodes to go to sleep immediately but also allows the intended receiver to send an early acknowledgment (ACK) to the sender so that the sender stops preamble transmission and starts transmitting the DATA frame immediately.

The unified power management architecture package for wireless sensor networks [44] implements a variation of X-MAC in TinyOS, in which the DATA frame itself is used as the short preamble. The idea presented in WiseMAC [45] can help BMAC and X-MAC further reduce energy consumption. A node with WiseMAC learns the wakeup schedules of a direct neighbor based on the ACK frame to a DATA frame the node sent to the neighbor. With this information, the sender for its next DATA frame to this receiver estimates when the receiver will wake up next. The resulting shortened preamble greatly helps to save energy and improve channel utilization.

PHY-Aided Transmitter-Initiated Duty-Cycle MAC: Recently, researchers have begun leveraging new PHY-layer techniques to improve efficiency of transmitter-initiated duty-cycle MAC protocols.

As illustrated in Fig. 7, when a sensor node performs a clear channel assessment (CCA) check, environmental noise, such as WiFi transmission over the air, is detected as legitimate activity on the channel. This problem is called false wakeup in [46]. The false wakeup causes the sensor node to remain awake even when no transmissions occur. As the ISM bands are often crowded, the false wakeups can significantly increase the energy consumption.

To solve this problem, the authors in [46] presented an adaptive energy detection protocol (AEDP), which dynamically adjusts a node's CCA threshold to reduce false wakeups caused by environmental noises. AEDP is efficient in reducing wakeups and thus improves network reliability and lifetime.

It is often very costly in latency and energy consumption to recover a transmission failure in a contention-based duty-cycling MAC protocol. This is because a retransmission may have to be withheld until its intended receiver wakes up in the next cycle. For an environment with interference and noise, robust packet transmission and recovery schemes described in Section II-A3 can help to reduce the retransmissions and the associated costs.

2) Receiver-Initiated Duty-Cycle MAC Protocols: Receiver-initiated duty-cycle MAC protocols attempt to improve network performance and lifetime by avoiding the long-lasting preamble transmissions of the transmitter-initiated duty-cycle MAC protocols.

For example, in RI-MAC [47], a sender does not occupy the medium until the intended receiver is ready for receiving, by using receiver-initiated transmission. This property allows RI-MAC not only to achieve comparable performance to X-MAC

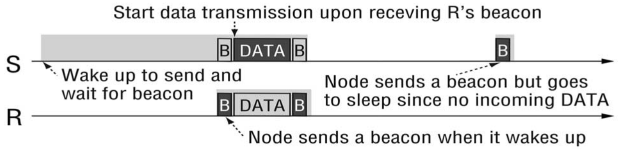

Fig. 8. Overview of RI-MAC.

under light traffic load, but to handle a wide range of traffic loads more efficiently.

In Fig. 8, a DATA frame transmission in RI-MAC is always initiated by the intended receiver node of the DATA. Each node periodically wakes up based on its own schedule to check if there are any incoming DATA frames intended for this node. After turning on its radio, a node immediately broadcasts a beacon if the medium is idle, announcing that it is awake and ready to receive a DATA frame. A node with pending DATA to send, node S in this figure, stays active silently while waiting for the beacon from the intended receiver R. Upon receiving the beacon from R, node S starts its DATA transmission immediately.

RI-MAC significantly reduces the amount of time a pair of nodes occupy the medium before they reach a rendezvous time for data exchange, compared to the transmitter-initiated protocols. This short occupation of the wireless medium enables more contending nodes to exchange DATA frames with their intended receivers, which helps to increase capacity of the network and thus potential throughput.

PHY-Aided Receiver-Initiated Duty-Cycle MAC: A-MAC presents an efficient way to resolve collisions based on nondestructive collision of ACK frames for receiver-initiated duty-cycle MAC protocols [48].

When there are multiple simultaneous senders, the receiver with RI-MAC relies on the capture effect [24] or energy detection right after beacon transmission to detect collisions. If energy is detected after the beacon transmission but no valid packet is received in a predefined time window, the receiver assumes that multiple contending senders have caused collisions and thus sends another beacon with a larger backoff window to instruct the senders to avoid collisions using random backoff.

A-MAC introduces simultaneous ACK transmissions following the beacon frame to detect and resolve collisions as shown in Fig. 9. When senders $S1$ and $S2$ receive the beacon from the intended receiver R, each of them sends an ACK after a fixed Receiver (RX)–Transmitter (TX) turnaround time. Although the ACK frames collide, they do so nondestructively, so the receiver R correctly decodes their superposition as a valid frame and concludes that traffic is pending. Then, R retransmits a beacon with an explicit contention window to instruct potential transmitters to do random backoff before new retransmission attempts, which help to resolve collisions between $S1$ and $S2$. In this way, A-MAC efficiently detects and resolves collisions.

The recent Strawman protocol [49] introduces an explicit collision signal to resolve collisions more efficiently under high traffic loads. In Fig. 10, after receiving a beacon B from their intended receiver, the senders simultaneously transit a special packet called COLLISION packet with randomly picked lengths. At the end of the COLLISION packet transmissions, the receiver sends a decision frame (D in the figure) that includes the length of the longest COLLISION packet transmission. $S2$ finds that the length matches the length of its last COLLISION packet transmission and thus starts data transmission immediately. In constrast, $S1$ finds that the duration does not match, so $S1$ will refrain from any transmissions. This mechanism is beneficial when the number of contending transmitters is large or data frames are long.

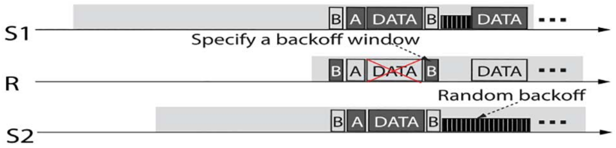

Fig. 9. Collision resolution in A-MAC

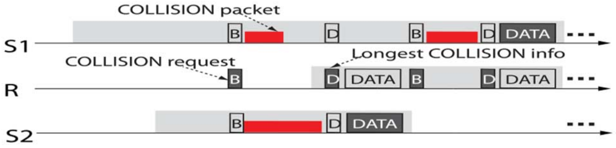

Fig. 10. Collision resolution in Strawman.

The simultaneous polling techniques [26], [27] discussed in Section II-A3 are general to be applied to contention-based MAC protocols. These can further improve the efficiency of collision resolution by providing an efficient mechanism to identify the IDs of multiple contending senders.

Unlike MAC protocols which can only tell if any collision has occurred, MACs using the PHY features like those in [26] and [27] enable a receiver to learn which neighbors have pending packets. This effectively allows the receiver to schedule the transmissions of neighboring nodes. Robust packet transmission and recovery schemes described in Section II-A3 can also benefit receiver-initiated duty-cycling MACs in minimizing energy and latency associated with retransmissions.

B. Contention-Free Duty-Cycle MAC Protocols

Contention-free MACs eliminate medium contentions and packet collisions by preallocating/scheduling nonoverlapping medium resources to participating sensor nodes. In contention-free MACs, the wireless medium could be partitioned based on TDMA, frequency division multiple access (FDMA), or code division multiple access (CDMA).

The deterministic zero-collision nature ensures high throughput, bounded end-to-end delay, and significant energy savings. However, contention-free MACs could incur significant overheads in the resource allocation, especially for sensors with dynamic data traffics or topologies. In this section, we review some of the latest contention-free MACs and corresponding PHY enhancements.

1) TDMA Contention-Free MAC Protocols: Time is divided into nonoverlapping TX slots and each of the sensor nodes are given some unique slots for transmissions. A receiver node needs to listen at the beginnings of all the TX slots of the sender node. If a transmission is not detected at the beginning of a specific TX slot, the receiver node can save energy by powering off its radio for the remaining time of the slot.

Using time slots to coordinate data transmissions requires accurate timing of all the participating nodes. To combat clock drift and timing errors, all the nodes must periodically synchronize to a global reference clock. To quickly adapt to network traffics, packet sizes, and topology changes, the allocations and the durations of the time slots need to be adjusted dynamically and frequently, significantly increasing the energy consumption and lowering the overall throughput of TDMA-based contention-free MACs. However, if networks have fixed traffic patterns, more efficient static slot allocation schemes could be used [50].

The point coordination function (PCF) of 802.11 [51] uses the access point (AP) as the central coordinator to assign time slots. This centralized scheme works for both static and mobile networks but is limited to topologies where all the nodes are in communication range with the central coordinator.

To address this limitation, one can construct a hierarchical slot allocation scheme (tree) on top of the basic centralized scheduler and optionally use techniques such as graph coloring to allow spatial reuse of time slots [52]. However, such hierarchical schemes are difficult to scale to networks with large numbers of sensors nodes.

TRAMA [53], EMAC/LMAC [54], and eL-MAC [55] employ a distributed time slot assignment mechanism that allows the spatial reuse of time slots. Under such a mechanism, nodes periodically exchange neighboring information to construct their 2-hop neighbor lists. The total number of messages needed to exchange 2-hop neighbor information is in the order of $O(N^2)$, where N is the network size. To reduce the messaging overhead, EMAC selects a subset of the nodes inside a network to join the allocation.

PHY Enhancements for TDMA Contention-Free MAC Protocols: Exchanging clock synchronization messages among the sensor nodes could significantly increase the energy consumption. This is especially an issue for networks that use static slot assignment schemes since clock synchronization messages could not be piggybacked to slot allocation messages which are frequent under dynamic schemes.

To address this problem, some PHY-based energy-efficient clock synchronization approaches have been proposed. In [56], radio data system clock signal in FM radio transmissions is exploited as a global reference for accurate clock synchronization. In [57], the time signals that are transmitted by some dedicated radio stations around the globe is used to provide access to the time reference with millisecond-level accuracy.

Sensor networks pose unique communication challenges including dealing with a very large number of nodes and traffic conditions (e.g., low duty cycle, bursty, and event-driven traffic). This difficulty can be alleviated by employing PHY-aided time slot scheduling techniques [26], [58].

In [26], a fast energy level detection designed to adapt the time scheduling to a different traffic conditions (e.g., high, medium, or low traffics) is proposed. Provided the traffic conditions at each node, it is possible to optimize the energy level detection to maximize the achievable network-level throughput [58]. It is shown through numerical simulations [58] and a FPGA prototyping [26] that the PHY-aided TDMA contention-free MAC significantly outperforms the contention-based MAC.

2) FDMA Contention-Free MAC Protocols: Typical radios used for wireless sensor networks, such as the CC2420 [59], could operate over one of multiple orthogonal channels. FDMA contention-free MACs take advantage of this by assigning different TX channels to nodes. This enables parallel transmissions among the sensor nodes for increased throughput. Since different senders may use different channels, a receiver must coordinate with the senders to switch to the matching channels for packet receptions.

Channel assignment is fundamentally a distance-2 graph coloring problem [60]. Channel assignment could be either performed statically or dynamically. With static schemes, channels are assigned once at the beginning of the deployment. For example, the MMSN-MAC [61] provides an exclusive channel assignment scheme. Since the number of nodes within two hops could easily exceed the total number of available channels supported by the radio, pure FDMA MACs with static channel assignment have limited scalability in practice.

This is very different from static TDMA schemes which could potentially allocate time slots to every node in a network. To address this limitation, some static schemes [61], [62] relax the contention-free requirement and allow some channels to be shared. Dynamic channel assignment schemes could adapt to the network loads or topology changes by changing the channel assignment on demand or before each transmission. However, such dynamic schemes incurs significant overheads.

In practice, most of the existing dynamic FDMA schemes are constructed on top of contention-based [63] or TDMA-based [64] schemes. For example, MMAC [63] uses contention windows on a predefined control channel for nodes to dynamically select channels with RTS/CTS like messages. Y-MAC [64] runs on top of LMAC [54] over a shared base channel. When transmissions cannot be fit into a single time slot, additional contiguous slots are dynamically allocated over some different channels. A good summary of such schemes could be found in [65].

PHY Enhancements for FDMA Contention-Free MAC Protocols: Traditional radios used for wireless sensor networks are half-duplex which means a radio cannot send and receive at the same time over the same channel. Latest physical radio designs [66] have demonstrated full-duplex communication capability using signal inversion and cancellation technique. With full-duplex radio, a channel divides into two subchannels to transmit and receive at the same time.

In FDMA, the carrier synchronization among different nodes is essentially important. The distributed carrier synchronization techniques [8], [13]–[15] discussed in Section II-A2b can be applied to any distributed sensors. Especially, the MS architecture [8] where a designated master node coordinates the synchronization of slave nodes in time-division duplexing (TDD) can be adopted to gain fast phase and frequency synchronization. This technique requires minimum coordination overhead by leveraging channel reciprocity. Precise phase synchronization up to almost sure phase coherence can be attained [13]–[15].

3) CDMA Contention-Free MAC Protocols: CDMA-based contention-free MACs work by assigning different orthogonal codes to nodes. CDMA-based contention-free MAC is not commonly used for wireless sensor networks due to the synchronization overhead [67]: all parallel transmissions need to be received by the receiver at the same time. TX power control may introduce additional overhead [67]. To address the limitations, a hybrid approach that combines CDMA with TDMA has been proposed [68].

PHY Enhancements for CDMA Contention-Free MAC Protocols: Although CDMA introduces significant overheads, it could be very efficient in sending a small amount of control data. The probe and pull MAC (PPMAC) [27] uses orthogonal Zadoff-Chu (ZC) sequences for a group of nodes to send control signals to the requester in parallel. The nice cyclic cross-correlation feature of ZC sequence makes the detection significantly simple and makes the tight synchronization requirement relaxed.

However, the parallel control signal transmission still demands TX power control to combat the near-far effect. This issue can be resolved by adopting a proper adjustment of cyclic shift dimension of ZC sequences with the long-term power control [28].

C. *Hybrid Duty-Cycle MAC Protocols*

Many duty-cycle protocols cannot be strictly classified as either contention-based or contention-free protocols. Still, they can benefit from the recent mechanisms based on PHY features discussed above. For example, S-MAC [41] employs clock synchronization among neighborhood (e.g., [4]).

Some MAC protocols may benefit from multiple aforementioned mechanisms. For example, EM-MAC [69] is a receiver-initiated contention-based duty-cycle MAC protocol. A sensor node with EM-MAC also learns the wakeup time and channel of a neighbour based on the neighbor's clock.

With WiseMAC [45], all sensor nodes are defined to have two communication channels. Data channel is accessed with TDMA method, while the control channel is accessed with carrier sense multiple access (CSMA) method.

Table II summarizes the major low-power duty-cycling techniques discussed in this section and the recent cross-layer optimizations for them.

IV. SENSOR NETWORK STANDARDS FOR INDUSTRIAL APPLICATIONS

The practical applications that sensor networks generate have necessitated technical innovations in emerging sensor network standards. In the past years, various applications of sensors have reported in sensor network standards for industrial applications and machine-to-machine (M2M) communications.

The M2M communication systems have been deployed either over wireless or over wired media. It is considered as a building block for smart grid (e.g., utility metering and power grid control) and means to deploy a large-scale (e.g., nation-wide) monitoring and control infrastructure, thus bringing big opportunities for the information and communication technology (ICT) industry.

One of the oldest standards in M2M communications targeting sensor applications traces back to power line communication (PLC) [70], [71]. Initiated as a part of industrial standards, recent evolution of PLC provides a nation-wide monitoring and control. The wireless personal area networks (WPAN) standard IEEE 802.15.4 [72] and various derived standards [73]–[76] have become the main stream in the industrial wireless communications. Furthermore, the wireless local area networks (WLANs) standard IEEE 802.11ah has also been proposed for the recent growth in demand for M2M communications [29].

In this section, we investigate energy efficient designs that have been deployed in several emerging standards which are foundations of industrial applications.

A. *Power Line Communication (PLC) Standards: International Telecommunication Union (ITU) G.9903, ITU G.9904, ITU G.hnem, IEEE 1901.2*

Power lines infrastructure is ubiquitous since it has been installed around the world for almost a century. The PLC standards have emerged and practically deployed for smart grid and sensing applications, such as automated meter reading (AMR), demand response (DR), and pilot wire communication for electric vehicle (EV) charging system.

In principle, all of the techniques described in Section II can be deployed either over wireless or wired media. For instance, there is gradual progression to upgrade current PLC systems to multiple-input multiple-output (MIMO) wired systems by adopting spatial diversity techniques in Section II, further enhancing the power efficiency of PLC sensors [77]–[79].

Power consumption of these devices critically matters when a massive number of devices, e.g., 1–10 millions of utility sensors and/or meters, are attached to power lines. For example, in ITU G.9903 [80], on the frequency band of 154–403 kHz, which is dedicated for Japan, it is allowed to transmit signal up to 1.6 Vrms over 10 Ω resistive load, which results in 256 mW power on the load.

If there are 10 million of such devices to perform certain tasks, the total power consumption is approximately 2.5 mW and, therefore, to provide the power to these devices, we may need to build additional power plants. If the poser consumption is reduced to 5 mW for each device, the total power needed is 50 kW. Thus, the power efficiency and consuming low power for PLC sensors are essentially important for them to be operated.

The most attractive advantages of PLC sensors to consumers is that there is no additional wiring required other than already installed power lines. Moreover, it provides reliable links for various sensor applications, which is one of the most important requirements for smart grid applications. All of the components are reliably connected in any geographic location or environmental conditions.

However, since power line channels and induced noise are challenging, there has been a need to design more robust and reliable techniques increasing the transmission range and, thereby, consuming less power for robust communications.

TABLE II
MAJOR MAC DUTY-CYCLING TECHNIQUES AND RECENT CROSS-LAYER OPTIMIZATIONS FOR THEM

Major duty-cycling techniques	Category	Recent cross-layer optimizations
Transmitter-initiated [43]–[45]	Contention-based	Handling false wakeup and packet recovery in noisy environment [20]–[25], [46]
Receiver-initiated [47]	Contention-based	Resolving collisions and packet recovery [20]–[27], [48], [49]
TDMA-based [51]–[55]	Contention-free	Improving low-power clock synchronization and node scheduling [26], [56]–[58]
FDMA-based [61]–[64]	Contention-free	Utilizing full-duplex PHY capability and carrier synchronization [8], [13]–[15], [66]
CDMA-based [67], [68]	Contention-free	Reducing power and complexity for aligned RX [27], [28]

Currently most of emerging standards are using orthogonal frequency division multiplexing (OFDM), such as power-line related intelligent metering evolution (PRIME), which is ITUG.9904 [81], G3 (ITU G.9903) [80], IEEE 1901.2 [82] on FCC bands up to 500 kHz for various applications.

1) ITU G.9903 (G3): G3-PLC was originally developed using OFDM technology as an industrial standard on CENELEC A band (36–91 kHz), and now they become international ITU standard extending their frequency band of operation upto 500 kHz [80]. For robust and reliable communications, G3 employs concatenated codes with convolutional code and Reed–Solomon (RS) code.

G3-PLC supports a mesh network and a robust mode for reliable communications [e.g., medium-voltage/low-voltage (MV/LV) communications]. This feature extends its transmission range significantly and reduces the necessitated transmission power of PLC devices, enabling an energy efficient large-scale monitoring.

2) ITU G.9904 (PRIME): PRIME PLC was developed also using OFDM technology as an industrial standard on CENELEC A band optimized for high data rate applications [81]. PRIME can achieve good coverage of the metering rooms connected to each distribution transformer. The PRIME standard handles low quality links at the MAC level, by promoting an intermediate node to be a switch.

PRIME Alliance started to develop robust PHY modes, which include symbol repetition concatenated with convolutional code and support tree topology networks. PRIME supports the data rates upto 1 mb/s for an uncoded mode, and 500 kb/s for a coded mode.

3) IEEE 1901.2: IEEE 1901.2 [82] started with G3-PLC as the baseline and it introduced new features/modes to improve MAC-layer and PHY-layer reliability and power efficiency. PHY improvements include coherent modulations, robust header using coherent modulations, long preambles for better preamble detection, long cyclic prefix to combat large channel delay spread, high modulations such as 16QAM for higher throughput, and full-packet interleaving to combat impulse noise aggressively. IEEE 1901.2 also provides a coexistence mechanism with other narrowband OFDM PLC standards.

B. IEEE 802.15.4: 802.15.4g and 802.15.4e

The 802.15.4 [72] category is probably the largest standard for low data rate WPANs. The IEEE 802.15.4 standard defines the PHY and MAC layer specifications for low data rate wireless devices with very limited battery consumption requirements. The basic standard with the most recent updates and enhancements is 802.15.4e [74] for industrial applications, and 802.15.4g [73] for smart utility networks (SUNs). All of these versions use the same base radio technology and protocol, defined in 802.15.4a/b [83].

IEEE 802.15.4 PHY employs direct sequence spread spectrum (DSSS) modulation. It is highly tolerant of noise and interference. It offers coding gain to improve link reliability. Reliable BPSK is used in the low data rate versions (20 kb/s), while offset-quadrature PSK (O-QPSK) is used for the higher-data-rate version (250 kb/s). Since O-QPSK has a constant wave envelope, more power-efficient amplifier techniques can be used to minimize power consumption.

IEEE 802.15.4 adopts CSMA with collision avoidance (CA). Most transmissions are short packets that occur infrequently for a very low duty cycle ($< 1\%$), minimizing power consumption. The minimum power level defined is -3 dBm or 0.5 mW. Most modules consumes 0 dBm (1 mW). However, some 20 dBm (100 mW) modules are available.

Recent studies reveal that the CSMA-CA-based MAC protocol suffers from unreliability and energy inefficiency if a nonappropriate parameter setting is used. Hence, various solutions have been proposed to select appropriate parameter values for CSMA-CA MAC [84]. Appropriate duty cycle and beacon interval [85] and adaptive collision resolution and traffic scheduling [86], which are similar to Strawman protocol [49], are proposed to maximize energy efficiency.

1) IEEE 802.15.4e (MAC Enhancement): IEEE 802.15.4e [74] enhances and adds functionality to the IEEE 802.15.4 MAC to better support the industrial applications. One remarkable feature of 802.15.4e amendment is the time-slotted channel hopping (TSCH) technique. TSCH was designed to allow IEEE 802.15.4 devices to support a wide range of industrial applications, which adopts time synchronization to achieve ultra low-power operation and channel hopping to enable high reliability for sensor nodes.

TSCH does not amend the PHY-layer, i.e., it can operate on any IEEE 802.15.4-compliant hardware. Similar to PCF of 802.11 [51], E-MAC [54], and eL-MAC [55], it allows adaptive resource allocation between neighbor nodes to the data traffic conditions. In [85], an adaptive synchronization approach is proposed and implemented as a part of IEEE 802.15.4e in the open wireless sensor network (OpenWSN) protocol stack.

IEEE 802.15.4e provides two contention-based low-energy mechanisms, i.e., coordinated sampled listening (CSL) and receiver initiated transmission (RIT). CSL allows a receiving device to periodically sample the channel(s) for incoming frames with a low duty cycle, which falls into the category of transmitter-initiated duty cycling in Section III-A1. In RIT, a receiving device periodically broadcast data request frames, and a transmitting device only transmits to the receiving device upon receiving a data request frame. RIT falls into the category of receiver-initiated duty cycling in Section III-A2.

Being standardized, CSL and RIT are being used in practical scenarios where noise and collisions are likely to occur. In these scenarios, we expect the cross-layer optimizaiton techniques in Sections III-A1 and III-A2 to get wider adoption.

2) IEEE 802.15.4g (PHY Amendment): It defines PHY amendment to the IEEE 802.15.4 to adopt smart metering utility network (SUN) and can also be extended to other sensor network applications. The PHY specification can be divided into three main communication technologies: 1) Gaussian frequency shift keying (GFSK); 2) OFDM; and 3) OQPSK. GFSK is already deployed in North America. Due to low peak-to-average ratio (PAPR) nature of FSK, it reduces transmit power level, resulting in enhanced power efficiency.

The achievable data rates are from 50–800 kb/s depending on the regions. The PHY design takes outdoor Doppler-frequency shifts into account in the pilot design, where the scattered pilots are employed to support real-time channel tracking.

C. ZigBee, WirelessHART, and ISA 100.11a

There are various standards derived from IEEE 802.15.4 for the industrial communications, such as ZigBee, wireless highway addressable remote transducer (WirelessHART), and International Standard on Automation 100.11a (ISA100.11a).

ZigBee standard aims to provide a cost-effective and low-power solution for the applications of building automation, security systems, remote control, remote meter reading, and computer peripherals. Both WirelessHART and ISA100.11a, protocols are developed and used to control and automate wireless industrial processes that are technically difficult or uneconomical to achieve using conventional wired system.

1) ZigBee: ZigBee is probably the most widely deployed enhancement to the 802.15.4 standard. It is a specication for the higher protocol layer and builds upon the MAC and PHY specifications in the 802.15.4. The enhancements include authentication, encryption for security, and a data routing capability that enables mesh networking. Since late 2004, ZigBee has proven its success, at least in the industrial domain where reliability and security are uttermost important.

To improve the energy efficiency of ZigBee, the parameter tunings [76] and the strobed preamble and early acknowledgement design [87] by modifying the enhanced power saving feature in X-MAC [43] have been proposed.

2) WirelessHART and ISA 100.11a: Both WirelessHART [75] and ISA100.11a [88] implement the 802.15.4 PHY [72]. A combination of DSSS and frequency-hopping spread spectrum (FHSS) is used as modulation technique, which makes both the standards more robust to interference in harsh industrial environments. A combination with OQPSK modulation allows for a raw bit rate of 250 kb/s. The maximum transmitted power is limited to 10 dBm (10 mW).

The MAC sublayer of WirelessHART and ISA100.11a is a subset of the 802.15.4 MAC [72]. The MAC extension includes changes to the CSMA-CA mechanisms by including additional spatial, frequency, and time diversity. For instance, TDMA combined with frequency hopping is used for channel access. To enhance energy efficiency of WirelessHART, a CCA-enabled TDMA can be used to support bursty and acyclic sensor traffics.

D. IEEE 802.11ah

IEEE 802.11ah is the evolution of WLAN standard to support WiFi enabled sensor node deployment. The OFDM-based PHY is capable of supporting multiple antennas on the downlink and various single user and multiple user diversity techniques [29]. The PHY data rate is at least 100 kb/s with coverage of 1 km.

IEEE 802.11ah MAC can manage a large number of nodes beyond 2000 for outdoor applications. It also provides enhanced power saving mechanisms for battery-powered sensor nodes with long replacement cycle. Though the 802.11ah does not employ energy efficient modulation schemes (e.g., GFSK and OQPSK in 802.15.4g), it rather achieves high power efficiency from innovative MAC design.

IEEE 802.11ah PHY is basically a 10 times down-sampled version of the regular WiFi. In particular, the 1 MHz OFDM PHY employing 2 symbol repetition aims to achieve 1 km outdoor coverage. It also includes the traveling pilots, which is also adopted in IEEE 802.15.4g [73], to combat outdoor Doppler-frequency shifts. The advanced time synchronization techniques (e.g., [4]) are employed to calibrate clock drifts.

The MAC supports various power saving operations. A power saving poll (PS-Poll) is allowed, which is similar to RI-MAC operation [47]. It also supports maximum idle period of a node to be set to a longer value (e.g., a couple of days, a week). In the uplink channel access [29], the access point can schedule sensor nodes for their sensor data delivery within the restricted access window (RAW). The RAW is divided into time slots and nodes determine its channel access slot assigned by the access point, similar to [48], [49]).

Special encoding and decoding mechanism for traffic indication map (TIM) that supports thousands of sensor nodes are proposed [29]. To further enable power saving, short control frames, e.g., short beacon, short ACK, short clear to send (CTS), short request to send (RTS), and short PS-Poll [29] are adopted.

IEEE 802.11ah includes various use cases such as internet of things (IoT), M2M, and smart grid communications. The performance and energy consumption of IEEE 802.11ah radio for IoT and M2M use cases were studied and different traffic patterns for M2M use case was evaluated in [89]. It is reported that the virtual grouping [90] and the Offset Listen Interval (PS-OLi) approach [91] can significantly enhance power saving and resolve the contention problems.

V. SUGGESTED RESEARCH DIRECTIONS

In this section, we describe, based on our treatment in the previous sections, various research directions in MAC and PHY layers, which we believe, have great potential to further enhance the energy efficiency of future sensor networks.

The diversity techniques in the aforementioned standards typically implement centralized approaches. As discussed in

Section II-A2, there are distributed techniques that tradeoff between performance and required overhead. Various practical approaches exploiting low-overhead feedback that enables coherence processing between distributed sensor nodes are available [13], [15], [92]. Most of these works, however, are for the equal gain transmission, as described in Section II-A2b.

The maximum SNR beamforming has received less attention. The area of distributed maximum SNR beamforming with the use of feedback is still a fertile ground for future research.

As aforementioned, various diversity techniques that have been developed in wireless communications also can directly be applied to wired technologies such as PLC sensors. The research on practical MIMO diversity techniques in the wired media is in its early stage and there have been a limited number of studies [77]–[79] in PLC sensor arena.

The wired MIMO research requires further study on suitable statistical channel models, e.g., the time evolution due to AC mains and periodic/correlated impulse noise. Once with the efficient wired-MIMO techniques, the reliability and power efficiency of PLC and/or wired sensors can be significantly enhanced.

For the transmitter-initiated, receiver-initiated, and TDMA-based duty-cycling techniques in Sections III-A1–Section III-B1, respectively, the cross-layer optimizations are focused on more practical issues such as false-wakeup, collision resolution, and clock synchronization. As these techniques have been adopted in recent IEEE standards as in Section IV-B1, future research in these areas may gain more attractions.

As described in Section III-B1, TDMA-based duty-cycling protocol can significantly benefit from recent PHY techniques. For the FDMA-based and CDMA-based duty-cycling techniques we expect that more research on cross-layer optimizations will be conducted as the PHY techniques get mature.

Various power saving mechanisms [47]–[49] under the contention-based MAC were discussed in IEEE 802.15, 802.15e, and 802.11ah. A major challenge with contention-based MAC is that distributed control creates unfairness and inefficiency in terms of throughput and latency, especially when thousands of sensors contend for the channel simultaneously. Hence, scheduling and contention resolution techniques discussed in Section III-B are becoming paramount important.

It is still a challenge to implement these techniques efficiently on low-power sensors in a practical manner. In certain applications, robust delivery of control data can become essential. In order to address all these challenges, we may need to develop some adaptive methods that combine both contention-based MAC and contention-free MAC.

Sensor data fusion techniques in Section II-B treat the network like a collaborative estimator cluster, leveraging high performance, but low complexity, estimation techniques. Unfortunately, the performance of these high-end estimation frameworks largely depends on the reliable medium access and allocation. Research has been focused on Gaussian additive noise channel. A few research has been conducted for a fading channel [36]. The development of collaborative data fusion techniques encountering medium allocation/scheduling strategies and practical medium remains a topic of interest.

VI. CONCLUSION

In this paper, we presented an overview of sensor network MAC and PHY techniques. Interest in applications of smart environment technologies will grow rapidly and create new standardis for various different networks and applications.

Many challenges remain. At the forefront are questions related to cross-layer design that are capable of handling a wide range of bursty and event-driven sensor traffics with low latency and high energy efficiency. This problem may or may not be tractable.

Traditionally, PHY-layer techniques and MAC protocols in sensor networks have evolved independently. There has been some seminal work taking enhanced PHY features into reliable MAC design. However, it is still complicated by issues such as the fundamental limitations in distributed processing, the tradeoff between energy consumption and performance, the effect of scheduling/contention resolution mechanisms, and the absence of a theoretical framework for the throughput and energy optimization that encompasses both the MAC and PHY features. These issues must be further investigated and, hopefully, be resolved in near future.

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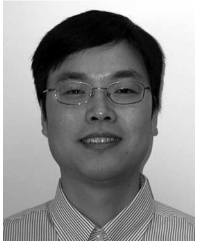

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