A Survey of Beacon-Enabled IEEE 802.15.4 MAC Protocols in Wireless Sensor Networks

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***Abstract*—IEEE 802.15.4 is the de facto standard for Wireless Sensor Networks (WSNs) that outlines the specifications of the PHY layer and MAC sub-layer in these networks. The MAC protocol is needed to orchestrate sensor nodes access to the wireless communication medium. Although distinguished by a set of strengths that contributed to its popularity in various WSNs, IEEE 802.15.4 MAC suffers from several limitations that play a role in deteriorating its performance. Also, from a practical perspective, 80.15.4-based networks are usually deployed in the vicinity of other wireless networks that operate in the same ISM band. This means that 802.15.4 MAC should be ready to cope with interference from other networks. These facts have motivated efforts to devise improved IEEE 802.15.4 MAC protocols for WSNs. In this paper we provide a survey for these protocols and highlight the methodologies they follow to enhance the performance of the IEEE 802.15.4 MAC protocol.**

***Index Terms*—Wireless Sensor Networks; Beacon-Enabled IEEE 802.15.4; Medium Access Control; Binary Exponent Backoff; Fairness; Power Consumption; Reliability; Throughput.**

I. INTRODUCTION

THE IEEE 802.15.4 (802.15.4 for simplicity) standard is the de facto set of specifications recommended to operate WSNs. The broad range of applications inspired by the advent of WSNs, along with the different performance requirements of these applications, have enticed the research community to focus on enhancing 802.15.4 MAC to mitigate its shortcomings. 802.15.4 MAC has been under the scope of research interest for more than a decade, with different objectives motivating the different research groups. These objectives include mainly reducing power consumption, improving channel utilization/throughput, improving packet delivery ratio/reliability, reducing the probability of collision, and reducing end-to-end delays. In achieving these targets, different approaches have been proposed, and this paper aims at surveying and discussing these proposals. It is worth mentioning that previous works have considered surveying WSNs [1-3]. However, the scope of [1] and [2] does not focus on 802.15.4 MAC and the problems that are inherent in it. They have conducted thorough surveys of the different aspects of WSNs with no specific treatment to the MAC protocol. On the other side, although the research objectives of [3] coincide with ours, its coverage is not as thorough as ours; the authors review a limited number of protocols and categorize them into three general categories. In our study, however, we provide a significantly broader coverage of the protocols available in the literature. The long list of protocols we survey enables us to distinguish the rationale behind the design of each protocol, and therefore, introduce a new detailed categorization of 802.15.4 MAC protocols. This categorization can better reflect the true advances and the state-of-the-art in this area of research. It can also make it easier to highlight what applications can be supported by which protocols. The rest of this paper is organized as follows. Section II provides an overview of the 802.15.4 MAC protocol and highlights both its strengths and weaknesses. Section III focuses on the challenge of having 802.15.4-based networks operate in a heterogeneous environment in which it coexists with other wireless networks operating in the ISM band. The section provides an overview of many solutions that worked on resolving the coexistence problem. These solutions have been criticized to highlight their strengths and limitations. Section IV introduces a novel categorization of the methodologies followed by different researchers to improve the 802.15.4 MAC, and then surveys the available MAC protocols in the literature. Finally, Section V concludes this paper.

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II. OVERVIEW OF THE IEEE 802.15.4 MAC PROTOCOL

The 802.15.4 standard defines the specifications of the PHY layer and the MAC sub-layer for low-rate personal area networks (LR-WPANs) [4]. The standard operates in either of two modes depending on the type of the CSMA-CA mechanism employed. If unslotted CSMA-CA is used, the standard will operate in a non beacon-enabled mode. In case the slotted CSMA-CA is used, the standard will operate in a beacon-enabled mode. Our focus in this paper is on the latter mode[1]. In this mode a superframe structure is utilized to organize the communications over the wireless medium. The superframe is delimited by beacons that the Personal Area Network (PAN) coordinator (coordinator for simplicity) sends periodically to synchronize the nodes. The superframe is fully defined using a beacon interval (BI) and a superframe duration (SD). BI refers to the time between two consecutive beacons and is constituted by an active portion and an optional inactive portion. During the latter, the coordinator enters a low-power mode to conserve its power resources. The active period, however, corresponds to the SD and is divided into 16 time slots. The active portion is constituted by the contention access period (CAP) and the optional contention

[1]In the rest of the paper, the use of the terms 802.15.4 or standard refers solely to the 802.15.4 MAC protocol operating in the beacon-enabled mode, except when stated otherwise.

free period (CFP). The structure of the superframe is specified by two attributes, namely, the macBeaconOrder (BO) and the macSuperframeOrder (SO). The BO specifies the time period during which the coordinator can communicate the beacon frames. The SO specifies the duration of the active portion plus the beacon frame. The superframe structure for the beacon-enabled mode is illustrated in Fig. 1 [5].

The value of BO is related to the beacon interval (BI) as follows:

$$\textit{for } 0 \leq BO \leq 14$$
$$BI = aBaseSuperframeDuration \times 2^{BO} \text{ symbols}$$

where aBaseSuperframeDuration is the number of symbols constituting a superframe when the SO is set to zero [4]. If BO is set to 15, the value of macSuperframeOrder is ignored and beacon frames will not be sent except upon request. The SO specifies the duration of the active portion plus the beacon frame). The value of the SO is related to the superframe duration (SD) as follows:

$$\textit{for } 0 \leq SO \leq BO \leq 14$$
$$SD = aBaseSuperframeDuration \times 2^{SO} \text{ symbols}$$

During the CAP, nodes utilize the slotted CSMA-CA mechanism to contend for medium access. The slotted CSMA-CA employs the Binary Exponential Backoff (BEB) algorithm as a means to reduce the probability of collisions over the wireless channel. BEB operates as follows. Before any transmission attempt three parameters are initialized, namely, the Number of Backoff stages (NB), the Contention Window (CW), and the Backoff Exponent (BE). These parameters are initialized with zero, two, and macMinBE[2] , respectively. After that, the node backs off for a random duration selected from the range $[0, 2^{BE} - 1]$. Once the backoff period expires, the node proceeds for two Clear Channel Assessments (CCA1 and CCA2). The number of CCAs is controlled by the parameter CW, such that CCAs are conducted as long as CW is not zero. If either CCA reveals that the medium is busy, CW is reset to two. The CCAs are needed to check whether the wireless medium is free from any activity before commencing a transmission. Packet transmission starts only if the medium is found to be clear during the two CCAs (provided that the remaining time slots in the current CAP are sufficient to transmit the packet and its ACK. Otherwise, the node has to postpone the packet transmission to the next superframe). However, if either of the CCAs reveals that the medium is busy, the value of BE will be increased by one (up to a maximum of macMaxBE[3]) and the node backs off again (that is, NB is increased by one and can reach a maximum of macMaxCSMABackoffs[4]). If BE reaches its maximum, it cannot change unless a successful/failed packet transmission occurs or packet retransmission commences. In that case, BE is reset to macMinBE. The packet will be dismissed if macMaxCSMABackoffs is crossed, and the BEB process will start over. Once a packet is transmitted successfully, an ACK packet is sent back by the receiver node. If the ACK packet is not received, the node attempts (up to a maximum of macMaxFrameRetries attempts) to retransmit the packet. With every retry, the complete BEB procedure is re-applied. If macMaxFrameRetries[5] is crossed, the packet will be dismissed. The basic time unit used by CSMA-CA is the aUnitBackoffPeriod. In Fig. 2 we show the flow diagram of the slotted CSMA-CA mechanism.

TABLE I
DESCRIPTION OF IEEE 802.15.4 ATTRIBUES AND PARAMETERS

IEEE 802.15.4 Attributes and Parameters	**Description**
aUnitBackoffPeriod	Basic time period used by the CSMA-CA algorithm
BE	Backoff Exponent
BI	Beacon Interval
BO	Beacon Order
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CW	Contention Window
GTS	Guaranteed Time Slots
macMaxCSMABackoffs	Maximum number of backoffs allowed before declaring channel access failure
macMaxFrameRetries	Maximum number of transmission retries allowed after a collision
macMaxBE	Maximum value of BE
maxMinBE	Minimum value of BE
NB	Number of times a node has backed off
SD	Superframe Duration
SO	Superframe Order

The CFP is used to support QoS requirements (low latency, specific data bandwidths$\cdots$etc). The CFP is constituted by a number of Guaranteed Time Slots (GTSs) that the coordinator dedicates for certain nodes upon their request. GTSs start immediately following the CAP in the active portion of the superframe. The maximum number of GTSs a coordinator can assign is seven. A node with an assigned GTS has full access to the channel during its GTS. Nodes activity during its GTS should be completed before the start of the next GTS or the end of the CFP. All the attributes and parameters of 802.15.4 that described above are listed in Table I for easy reference (descriptions are taken from [4]).

The 802.15.4 MAC is distinguished by several strong aspects that are beneficial to WSNs. In particular, the employment of a backoff mechanism is an ingenious approach to conserve sensor nodes power resources while reducing

[2]macMinBE is a MAC attribute defined in the 802.15.4 standard with a default value of 3.

[3]macMaxBE is a MAC attribute defined in the 802.15.4 standard with a default value of 5.

[4]macMaxCSMABackoffs is a MAC attribute defined in the 802.15.4 standard with a default value of 4.

[5]macMaxFrameRetries is a MAC attribute defined in the 802.15.4 standard with a default value of 3.

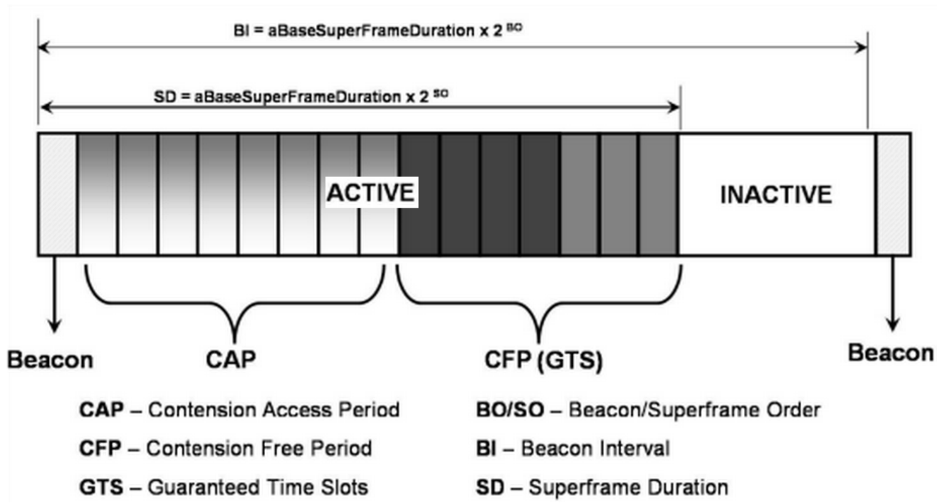

Fig. 1. Superframe structure [5].

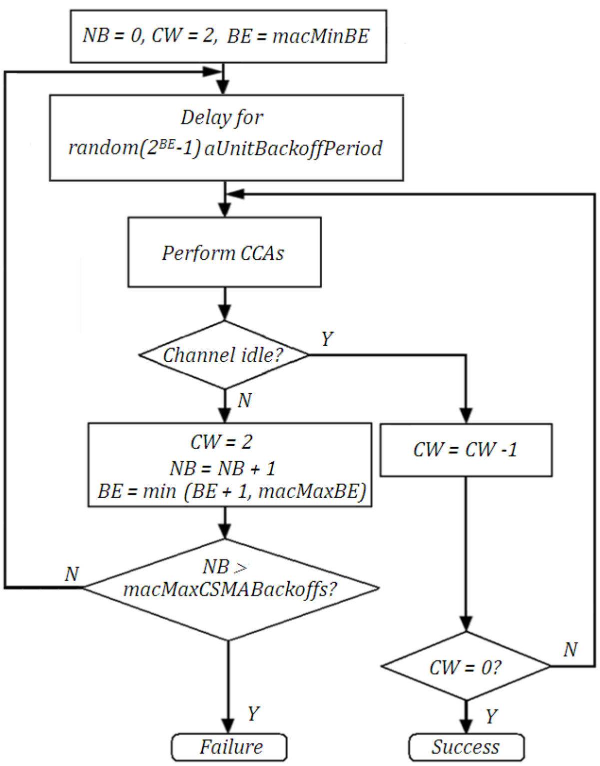

Fig. 2. CSMA-CA mechanism.

the likelihood of collisions over the communication medium. Nodes can conserve power because they remain in a sleep mode while waiting for an opportunity to contend for the medium. Having some nodes in the sleep state reduces the number of nodes that are about to conduct their CCAs, which reduces the probability of packet collisions. Also, the incorporation of two CCA periods is used as a means to protect the ACK packet against collisions.

In other words, if a node is performing its CCA1 at the same instant that another node has finished its packet transmission; the first node will sense the medium free. Therefore, in order to give the second node a chance to receive its ACK packet, the first node is required to perform another CCA. This way, 802.15.4 MAC has implicitly employed a priority-based approach in which the ACK packet is favored over other data packets. Furthermore, the idea behind incrementing BE, which is already adopted in IEEE 80.11, is to find its appropriate value that better adapts the duration of backoff to the level of activity over the communication medium. With that, nodes gradually adapt their duty cycles in a fashion that reduces the possibility of suffering from a collision. On the long-term, nodes will find themselves treated equally in terms of the chance to access the medium (long-term fairness).

However, we can identify several weaknesses in the 802.15.4 MAC protocol that can lead to deterioration in the performance. The selection of BE is quite random and does not take into consideration the number of nodes available in the network, the level of communication activity over the medium (at the time of selecting BE), and the likelihood of packet collisions. A node with a packet to send always increases BE gradually in the same manner (that is with steps of 1). This is done regardless of how long the node has been trying to access the medium, what traffic intensity is currently available over the medium, or how urgent the nodes traffic is. Also, BE is reset to its minimum after a successful transmission, discarding a packet, or exhausting the maximum number of transmission retries. This reset is done blindly without considering the reasons behind the failed (or the failed trials of) transmissions. In other words, the employed BEB is memory-less [6] as it keeps no information about the network status or conditions. Besides, we may encounter situations where nodes are sleeping more than needed (because the selection of BE is random), and this may lead to having the medium idle for unnecessary extended periods of time. This has a direct impact on the throughput of the system.

Also, the functionality of BEB is mainly deterministic and responds slowly to the changes in the network (in terms of the size of the network, the intensity of the traffic loadetc). The algorithm lacks dynamic, adaptive capabilities that can optimize the duty cycle of the sensor nodes such that minimal power expenditure is experienced. Moreover, nodes that cannot complete their transaction during the current CAP are required to postpone their transmission to the beginning of the next CAP. The problem with this approach is that at the beginning of the next superframe we may have multiple simultaneous transmissions that are about to contend for the medium [7]. This situation leads to high probabilities of collisions that can degrade the throughput of the overall network. 802.15.4 MAC may also behave unfairly, on the short term, under saturation conditions (that is, when nodes have always packets to send) [8]. This can be seen from noticing that a node that fails to access the medium tends to backoff for longer periods (because BE keeps increasing as mentioned earlier), reducing its opportunity of sending its packets. However, a node that has just finished its successful transmission will reset its BE to its minimum, which results in shorter backoff periods and thus higher chances of accessing the medium. That is, in many situations, the last successful node may be favored on the account of other nodes [9]. Clearly, under saturation conditions we will face a high rate of packet collisions, which leads to excessive power consumption and degraded throughput [10].

802.15.4 MAC suffers also from the lack of any measures for prioritizing traffics or nodes. The only implicit prioritization considered by the standard is associated with the ACK packet, which is assigned a higher priority over other packets. No special rules are employed to classify traffics based on their urgency, or to classify nodes based on their persistency to access the medium. This behavior can burden nodes power resources as certain nodes, which may be persistent in their access attempts, may deplete their batteries at a higher pace than other nodes. When it comes to 802.15.4s support of time-sensitive WSNs, we can see the important feature of GTS that we described above. However, the design of this feature has several limitations. GTS resources are very limited; a maximum of seven GTSs are available in each superframe. This poses a major scalability problem for dense WSNs. Also, a GTS (which may span over 15 time slots) may be acquired by a node with a low arrival rate. This means that the GTS will be underutilized by the node and important network resources will be wasted. Furthermore, GTSs are granted on a first-come first serve basis, and therefore, nodes with high data rates are not favored over other nodes with less data rate requirements.

Another drawback highlighted in several studies is that 802.15.4 MAC does not address the hidden terminal problem. The latter refers to the fact that a node that is communicating with a target node may not be aware that another node, that it cannot hear because it is out of its transmission radius, is already transmitting packets to the same target node. As a result, packet collisions happen and retransmission procedures are initiated. These procedures lead to increases in power consumptions. Also, the hidden terminal problem affects the several QoS metrics, like, the throughput, reliability, and transfer delay (see [52] for more details). These functionality issues in 802.15.4 MAC are far from being acceptable in WSNs. Therefore, new strategies and algorithms are needed to mitigate many of these pitfalls such that a more efficient performance is achieved. Another aspect that requires a careful attention when it comes to practical deployment of 802.15.4-based WSNs is the aspect of coexistence with other wireless networks. The coexistence problem can highly affect the design of the 802.15.4 standard. This critical problem is discussed in the next section.

III. IEEE 802.15.4 in Heterogeneous Environments

In practical deployments, IEEE 802.15.4-based WSNs operate in the vicinity of other wireless networks that are based on different technologies. Such deployments face the challenge of interfering communications due to having these technologies operate, similar to 802.15.4, in the unlicensed Industrial, Scientific, and Medical (ISM) band at 2.4 GHz. Examples of these technologies include 802.11 (WLAN) and 802.15.1 (Bluetooth). Interference occurs when the operation of 2.4 GHz wireless devices overlaps in frequency, space, or time. This interference can severely affect the performance of the coexisting networks. Therefore, there is a need to mitigate the effect of interference that the 802.15.4 network will suffer from during its communications. There have been a considerable number of studies that tackled the problem of coexistence from the perspective of the 802.15.4 PHY layer (see for example [11]-[17]). From the 802.15.4 MAC perspective, we can highlight several important contributions too. Jung et al. in [18] propose an interference mediation scheme to resolve the coexistence of WLAN and ZigBee networks. The authors focus on the scenario where a ZigBee network is collocated with several WLAN networks such that the former cannot find an interference-free channel to commence its communications. To resolve this situation, the authors introduce an interference mediator (IM) that uses WLAN and ZigBee modules to coordinate the interference between these networks. The mediation scheme is composed of two parts, namely, the Channel Status Observation Part and the Interference Mediation Part. With the Channel Status Observation Part the IM examines the communication channel to assess the severity of interference the networks are encountering. If the severity crosses a pre-defined threshold, the Interference Mediation Part will be activated. The latter scans the available channels in an attempt to find non-overlapping ones, and then assigns them to the network that is mainly affected by the interference. In case no such channels are found, the Interference Mediation Part uses a novel TDMA-based interference mediation scheme that can preserve fairness in treating the available networks (especially the ones that are severely affected by the interference). Basically, the TDMA-based scheme allows for transmitting ZigBee data during the WLAN PCF duration while the WLAN data is transmitted during the inactive duration of the ZigBee. That is, the new TDMA-based scheme utilizes a new superframe structure to resolve the interference. The authors also define some schemes to select the ratio of time occupancy between WLAN and ZigBee networks in the new superframe. These schemes select the ratio depending on whether the available networks need to be treated fairly in terms of time, throughput, or per-data transmission. The authors provide a simulation study to evaluate the performance of their proposed schemes in terms of throughput and channel occupancy time. Their results show that the new interference mediation scheme can effectively reduce the effect of interference among collocated networks. We can highlight several problems with the scheme in [18]. The coordinator node is burdened with additional tasks to resolve the interference problem. The authors should have assessed the impact of these new tasks on the memory and power resources of the coordinator. Also, the scalability of the new scheme should be studied. In other words, what is the rate at which WSNs/WLANs are being denied admission to the region affected by interference and how can the new scheme reduce this rate? Furthermore, it is not clear whether the IM is a sensor node, with limited power resources, or a node with access to a rich source of power. If it is regular sensor node, there is a serious problem in how it utilizes its battery because it is supposed to manage both WLAN and ZigBee nodes without periods of sleep. On the other hand, if this is a resourceful node with no limitations on its power needs, the whole proposal becomes centralized and a serious scalability issue occurs. Yuan et al. in [19] propose a decentralized approach to mitigate the interference faced by 802.15.4 nodes. This approach is based on the adaptive and distributive adjusting of CCA thresholds in the presence of high levels of interference. The authors consider three scenarios of coexistence 1) 802.15.4 nodes and 802.11b/g nodes can sense each other, 2) Only 802.15.4 nodes can sense 802.11b/g nodes, and 3) Neither network can sense the existence of the other, but 802.15.4 nodes may still suffer from 802.11b/g interference when very weak 802.15.4 links exist. With scenario 1, if heavy 802.11b/g interference occurs, 802.15.4 nodes will suffer from high channel access failures and low collision incidents. In scenario 2, 802.11b/g can lead to both channel access failures and collisions. Finally, scenario 3 can only cause packet collisions. The problem of having excessive channel access failures is that nodes are forced to conduct repeated CCAs to send a single packet, and this leads to increases in power consumption. Therefore, in case of having coexisting of 802.11b/g networks, the authors target improving the performance of 802.15.4 networks by reducing the effect of interference that leads to channel access failures. This is done by controlling the Energy Detection (ED) thresholds that the CCA depends on to examine the energy level on the communications channel. In case of heavy interference, 802.15.4 nodes will increase their ED thresholds and this in turn reduces the number of channel access failures. On the other hand, as the interference diminishes, nodes will decrease their ED thresholds back to the initial values in order to balance the channel access privilege among all nodes. The authors finally provide simulations that show the ability of their new approach to improve the performance of the 802.15.4 nodes, in the presence of interference, in terms of throughput. The algorithm in [19] is proposed for peer-to-peer WSNs and the nodes are able to deal with the interference in a distributed fashion without any help from a designated coordinator node. However, the adjustment of the ED thresholds does not take into consideration the duty cycle of the 802.11b/g nodes, and this may lead to excessive collisions between the packets of the coexisting networks; the authors have already highlighted that their algorithm does not handle the problem of packet collisions due to networks coexistence. Furthermore, as the ED thresholds increase, some delays are encountered in delivering the packets and the study should have investigated this issue. Yuan et al. in [20] introduce a distributed, adaptive multi-channel MAC protocol that is capable of avoiding interference. This protocol enables a large-scale single channel ZigBee network to avoid interference by partially changing its operational channel. The new protocol consists of two phases, namely, the interference detection phase and the interference avoidance phase. In the interference detection phase, each node tracks the failures of channel access. Once the ratio of transmission failures and total transmission attempts becomes greater than a certain threshold, a node starts to conduct an energy scan on the current channel to see if the energy level has crossed another predefined threshold. If so, the node concludes that it is facing interference. This triggers the interference avoidance phase. In this phase, the node follows a selection algorithm to sequentially scan the energy in every channel until it finds an energy level below the aforementioned threshold. In case none of the channels has that energy level, the node will have to remain at its current channel. The selection algorithm forces the node to start scanning from at least four channels away from its current channel. This is because each 802.11b/g channel overlaps with four ZigBee channels. Once a node selects a new channel, it broadcasts its selection to its one-hop neighbors. Also, after changing to the new channel, the node will periodically update its neighbors about its new operational channel. This node, as it communicates with neighbors that still use the old channel, has the ability to continue tracking the channel access failures to see if the interference over that channel has disappeared. This way, the node has a chance to shift back to its original channel as long as the interference level is low. Simulations show that the multi-channel MAC protocol can achieve a strong performance in terms of improving the throughput and lowering the channel access failure rates. The problem with the protocol in [20] is that it may lead to a faster draining of a nodes power resources. This can be seen by noticing the requirement that a node should run a selection scheme to find an appropriate channel for its transmissions. Then, the node has to keep notifying its neighbors of its new channel. This is beside the process of tracking the state of the old channel in order to shift back to it. Tytgat et al. in [21] introduce the Coexistence Aware CCA (CACCA) concept as a means to support coexistence of different networks. The authors highlight the fact that all of the technologies that use CSMA-CA employ the CCA concept; however, it is tailored to the specific needs of the technology using it. Therefore, when different CSMA-CA-based networks are collocated, the CCA may decrease the probability that a network discover the availability of other networks. It may even contribute to the increases in cross-technology collisions. The CACCA concept allows nodes of a certain network to backoff for other coexisting networks to lower the level of interference. To realize the CACCA concept, the authors propose the use of a sensing engine, which is a fast and accurate device that measures spectral power density across a wide bandwidth [21]. The sensing engine can analyze a limited bandwidth within a very short time period, and therefore, can be used for fast and reliable detection of other networks. In other words, the sensing machine is employed to detect, for example, ZigBee networks reliably within the

Wi-Fi CCA time. In this context, the use of the sensing engine helps in reducing the ZigBee CCA time 32 times (from 128 s to only 4 s), which makes it equal to the Wi-Fi CCA time. Three different deployment alternatives are studied, 1) Deploy the sensing engine on the ZigBee side only, 2) Deploy the sensing engine on the Wi-Fi side only, or 3) Deploy it on both sides. The study shows that the latter alternative achieves the lowest level of ZigBee packet loss, which improves the reliability in consequence. The beauty of the proposal in [21] is that its power requirements are marginal on the sensor node platform. It also deals with packet loss, due to interference with 802.11b/g networks, in an intelligent and effective way. The protocol is also highly scalable. As the sensing engine supports a networks awareness of another, we expect that the packet loss due to channel access failures to reduce too (although this issue has not been investigated in the study). ElSawy et al. in [22] propose a distributed spectral sharing approach to deal with the coexistence problem among collocated IEEE 802.15.4-based WSNs. The proposed approach enables these WSNs to coexist and share a logical communication channel without compromising their efficiency. The authors firstly discuss the conditions and configurations that allow WSNs to operate in an overlap-free manner. The conditions are based on the fact that if we can carefully schedule the active period of a certain WSN to take place during the inactive period of another, with proper time offsets among the different WSNs, the operation will be overlap-free. Based on this discussion, the authors have described their coexistence approach as follows. WSNs are classified as interfering and non-interfering. Interfering WSNs are the ones that contribute a severe interference over the communication medium. These are major interferers that should be avoided while communicating. Avoidance can be guaranteed through the aforementioned conditions. On the other hand, non-interfering WSNs are those that contribute a negligible interference that can be tolerated. Distinguishing interfering WSNs from non-interfering ones depends on a threshold (called the coexistence threshold) that is used to test the level of power in the received beacon. In their simulations, the authors have considered single-channel and multi-channel scenarios. For the multi-channel scenario, a maximum of 4 channels has been assumed. A WSN can select a certain channel based on one of three suggested channel assignment techniques. The strengths of the approach in [22] are that it is fully distributed and it introduces no changes to the original standard. In both of the channel scenarios, the approach shows a superior performance in terms of supporting coexistence. On the hardware side, the approach requires no platform upgrades. However, although the approach is mathematically simple, yet efficient, the authors do not discuss the power requirements of this approach. Also, for the multi-channel scenario, no quantification has been provided regarding the delay and power costs associated with each of the channel assignment techniques. This is highly important because the authors highlight the fact that in one of the techniques the admission of a WSN may require scanning all of the available channels, which is necessarily accompanied with delays and power wastage. Kim et al. in [23] introduce the concept of a virtual channel as a means to increase the number of available communication channels. This concept allows for a better management of the spectral and temporal resources, and in turn, supports the coexistence of collocated WSNs. Contrary to the logical channel that is specified in the spectral domain, the authors define the virtual channel to be a channel that is specified in the spectral domain (frequency band) as well as the temporal domain (time duration and offset). Creating a virtual channel requires a careful scheduling of the superframes of the different collocated WSNs, and benefits from the fact that low duty cycle applications underutilize the available logical channels. Virtual channels are created iteratively in two steps: 1) a time schedule is specified, in terms of duration and offset, for a given set of logical channels, and then 2) the quality of the specified schedules is assessed to identify the most efficient virtual channel. The scheduling is accomplished through two proposed superframe schedulers, namely, the Scheduler Using Throughput Estimation (SUTE) and the Nearest Vacancy Search (NEVS). These schedulers are used to determine a proper time offset where a virtual channel is created. SUTE works on preparing a schedule that minimizes beacon collisions such that collocated WSNs can coexist with minimal interference; restricted overlap among superframes is allowed. NEVS, however, allows no overlap among the superframes of the different WSNs. In addition to these schedulers, the authors also introduce the Virtual Channel Selector (VCS) that is used to identify the best available logical channel to place the superframe into. Basically, VCS is constituted by three main steps, namely, WSN grouping, BO and SO adjustment, and logical channel selection. First, WSNs are grouped into sets that use the same logical channel (this is ought to minimize the number of utilized logical channels). Next, BO and SO are adjusted to have a better sharing of the resources among the WSNs. Finally, VCS selects the best logical channel and time offset to accommodate the incoming WSN. The strength of the work in [23] is that it efficiently achieves a significant increase in the available channels of communications (that is, introducing virtual channels in addition to the already available logical channels), which provides a boost to the support of coexistence. Furthermore, the management of the virtual channels is handled in a completely distributed manner, and can be fully implemented on the coordinator nodes (WSNs are assumed to be of a star topology) simply as a firmware add-on. It is an ingenious proposal that introduce marginal changes to the IEEE 802.15.4 standard. However, we notice that since the proposed algorithms are to be run on the coordinator node, it is highly important to investigate the cost of these algorithms in terms of power requirements (especially that the SUTE scheduler is not simple computational-wise). Also, the authors have not discussed the delay encountered to admit a new WSN. In their simulations, the authors have focused on only one metric (the throughput). However, the WSNs are assumed to be supporting diverse applications with different QoS requirements. The proposed algorithms do not take these requirements into consideration and treats any incoming WSN equally and regardless of the services it offers. It is essential to assess the ability of these algorithms to support these requirements through considering other performance metrics like delay, packet loss, and packet delivery rate.

Based on the descriptions of these approaches and the comments we have provided, we strongly advocate the use of distributive solutions for the coexistence problem (the work in [18] follows a centralized approach that burdens the power resources of the coordinator node). Such solutions preserve the self-organizing nature of WSNs. They also support the factor of scalability, which is inherent in the design of any WSN. On the other hand, solutions that are centered on intelligibly scheduling the superframes (like [22] and [23]) are highly favored as they introduce no modifications to the original 802.15.4 standard; careful attention should be given to the complexity of the scheduling approach as it should be lightweight to avoid any excessive power consumption. Solutions that concentrate on scanning the operational channel (like [20]) cannot be an effective remedy to severe interference situations because an 802.15.4-based WSN is limited in its scanning to only 4 channels. These solutions must be complemented with other schemes (like the TDMA-based scheme in [18]) to boost the performance. Moreover, proposals that focus on scanning the band should provide a clear idea about the costs in terms of power consumption (For example, the authors in [21] provide important details about the power expenditure of their system).

Another point that we would raise is the importance of defining the application that the WSN is serving and working on resolving the coexistence problem based on the applications requirements. It is difficult to devise a solution that can perform perfectly for every application. Instead, specifying the application can reduce the design requirements and constraints and opens an opportunity for customized solutions that can be controlled and managed more properly. On the other hand, this methodology may pave the way for cross-layer approaches in which the application layer dictates how the MAC and PHY layers should function to mitigate the interference.

It is quite apparent that coping with the coexistence challenge does necessarily require changes in the specifications and design of the 802.15.4 standard. Instead, smart scheduling of the superframes and/or upgrades to the hardware design of the sensor node platform are expected (as proven by the studies we have reviewed) to alleviate the effect of interference on the operation of the WSN. Although the coexistence problem is one of the main factors that can hinder the proper performance of the 802.15.4 MAC protocol, the protocol suffers from various weaknesses that can degrade its performance. In the next section we provide a detailed discussion of the approaches proposed in the literature to improve the 802.15.4 MAC protocol.

IV. Approaches to improve IEEE 802.15.4 MAC

We can categorize the available literature to improve the 802.15.4 MAC protocol as follows:

1) Parameter Tuning-based approaches: These approaches are in favour of minimizing the modifications made to the standard in order to benefit from its strengths in terms of supporting the distinguishing characteristics of WSNs. Therefore, they argue that superior performance can be achieved with the standard provided that its parameters are tuned properly. The benefit of these approaches is that they attempt to avoid introducing new overheads that may burden the sensor nodes platforms with additional power expenditures. The drawback of these approaches, however, is that they tend to be application-specific and may require the sensor nodes to solve optimization problems in order to find the best tuning of their parameters, which may lead to extra power consumptions. Examples of these approaches include [24], [25], [26], [27], [28], [29], [30], and [31].
2) Cross Layer-based approaches: These approaches advocate the collaboration and exchange of information among the different layers of the protocol stack such that a better tuning of the MAC layer parameters is achieved. While these approaches may not necessarily change the standard itself, they base its parameters configuration on the information provided by other layers, and thus excessive latency may be incurred. This is besides the overhead of changing the architecture of the protocol stack such that a new control channel or layer is used to convey the configuration data from a layer to another. However, the benefit of these approaches is that they work on having a comprehensive solution that optimizes the performance of the sensor node. Examples of these approaches include [32] and [33].
3) IEEE 802.11-based approaches: These approaches exploit the fact that BEB has been originally deployed in IEEE 802.11. Therefore, they migrate some solutions that have been proposed for IEEE 802.11 for deployment in the context of 802.15.4. These approaches anticipate that the solutions that have proven efficient in IEEE 802.11 should work properly in 802.15.4 networks. However, the main drawback of these approaches is that IEEE 802.11-based algorithms have not been designed considering the conservation of power as a primary requirement. The latter is a pivotal requirement for 802.15.4-based WSNs. An example of these approaches is [34].
4) Priority-based approaches: These approaches work on improving 802.15.4 MAC by recognizing the need to prioritize nodes access to the medium. These approaches highlight the fact that the standard does not have special measures to categorize nodes, based on the urgency of their traffics for example, such that nodes are treated equally and fairly. Examples of these approaches include [35], [36], [37], [38], [39], [40], and [41].
5) Duty Cycle-based approaches: These approaches work on managing nodes access to the medium during the active and inactive periods, of the superframe, such that it becomes more power-efficient. The advantage of these approaches is that they reveal additional opportunities to conserve more power in the WSN without compromising other important performance metrics. Examples of these approaches include [42], [43], [44], [45], [46], [47], [48], [49], and [50].
6) Backoff-based approaches: These approaches focus on improving the performance of 802.15.4 MAC through devising new backoff algorithms that can control the nodes medium access in a more efficient manner. Many of these approaches manage to make the backoff pro-

cess more adaptive and dynamic. Examples of these approaches include [51], [52], [53], [54], [55], [56], [57], [58], [59], and [60].

7) QoS-based approaches: These approaches target enhancing the GTS feature of 802.15.4 MAC. These approaches work on devising more efficient GTS allocation schemes that can assign GTSs in an optimized manner. The target is to achieve a better utilization of the bandwidth dedicated for the requesting nodes. Examples of these approaches include [61], [62], and [63].
8) Hidden Terminal Resolution-based approaches: These approaches enhance 802.15.4 MAC to make it more aware of the existence of hidden terminals. Examples of these approaches include [64], [65], and [66].

These categories are summarized in the diagram shown in Fig. 3. It should be mentioned that some of the approaches cited above can fall under more than one category, but we use the classification that better reflects the methodology followed by the approach. In the following subsections we review all of the above cited research works.

A. Parameter Tuning-Based Approaches

Anastasi et al. in [24] present a comprehensive analysis of the 802.15.4 MACs performance in terms of reliability. The authors argue that this MAC protocol suffers from what they call the 802.15.4 MAC unreliability problem. With this problem MAC performs poorly in terms of the proportion of packets that can successfully reach their destination. Basically, the authors blame the power management mechanism (attained by the utilization of CAP and CFP in the superframe), applied by 802.15.4 MAC to conserve the power resources of the sensor nodes, for this degradation in performance. This is confirmed through simulations that have studied the packet delivery ratio while power management is enabled or disabled. To overcome this pitfall, the authors conduct additional simulations to understand the impact of the 802.15.4 MAC default attributes (that is, macMinBE, macMaxBE, macMaxCSMABACKoffs, and macMaxFrameRetries) on the observed performance degradation. In particular, the authors define three sets of CSMA-CA parameters in their simulations, namely, the Default Parameters Set (DPS), the Standard Parameter Set (SPS), and the Nonstandard Parameters Set (NPS). DPS adopts the default parameter values as defined by 802.15.4 MAC. SPS uses the maximum values allowed by the standard. Finally, NPS depends on values that are beyond the standards allowed maximums. The conducted simulations show that NPS achieves a superior performance in terms delivery ratio and per packet energy consumption, although these come at the expense of increased latency. The main conclusion of this study is that improving the performance of the standards MAC can be achieved through proper tuning of its parameters; which requires a new set of allowed values. The benefit of this proposal is that it avoids any modifications to the core of the 802.15.4 standard and presents recommendations to enhance its overall behavior.

Park et al. in [25] propose an adaptive MAC sub-layer to minimize power consumptions, while achieving reliable and timely communications. They formulate an optimization problem with an objective function to minimize the total power consumption, subject to constraints on reliability and packet delivery delay. The decision variables are chosen to be the MAC parameters, namely, macMinBE, macMaxCSMABACKoffs, and macMaxFrameRetries. After presenting a generalized Markov chain model for the slotted CSMA-CA mechanism, under saturated traffic conditions, the authors provide numerical results that show how to properly tune the decision variables in order to prolong the lifetime of the network. The overall outcome is an adaptive MAC sub-layer protocol that conforms to the constraints of WSNs.

Zhao et al. in [26] propose the Power-efficient MAC (PeMAC) and the Bandwidth-efficient MAC (BeMAC) protocols to optimize 802.15.4 MACs performance. Each node runs these protocols to adjust its local contention parameters in accordance to the number of nodes in the network. The objective of PeMAC and BeMAC is to improve power-efficiency (the number of successfully transmitted bits-per-second-per-Watt) and bandwidth efficiency (the number of successfully transmitted bits-per-second), respectively. The authors derive mathematical expressions that relate each of these efficiencies to the transmission probability (which is a function of the network size). These expressions are beneficial in determining, given a network size, the optimal transmission probability at which maximum power and bandwidth efficiencies can be achieved. The size of the network, however, is not a directly controlled variable, and therefore, the nodes should estimate this size. This means that there is a need use adaptive techniques that can tune the contention parameters such that the optimal performance is achieved. These facts lead the authors to implement a look-up table at each node to compute its contention parameters based on the estimated size of the network, and therefore, achieve the targeted optimal performance. The overall performance of PeMAC and BeMAC is evaluated against 802.15.4 MAC through simulations. The collected results show that proposed protocols manage to improve both power and bandwidth efficiencies especially for large network sizes.

Pollin et al. in [27] provide a comprehensive, analytical evaluation for the slotted CSMA-CA algorithm in the presence of acknowledged and unacknowledged uplink data transmissions, under both saturated and unsaturated conditions. A Markov-based model is developed and the performance of the standard in terms of power consumption and throughput is analyzed. They describe guidelines to tune the MAC parameters, namely, macMinBE and NB, to increase throughput and power savings.

Lee et al. in [28] propose the Superframe Adjustment and Beacon Transmission Scheme (SABTS) that aims at resolving the problem of collisions between beacons themselves as well as between beacons and data frames in cluster tree-based WSNs. SABTS works on controlling the values of the BO and the SO for the PAN coordinator, cluster coordinators, and sensor nodes. It also decides on the accurate timing for transmitting beacons for the PAN coordinator and cluster coordinators. Basically, SABTS ensures that different starting times of beacon transmission are defined such that coordinator nodes can avoid beacon collisions. This is attained through computing the BO and SO for the PAN coordinator at the

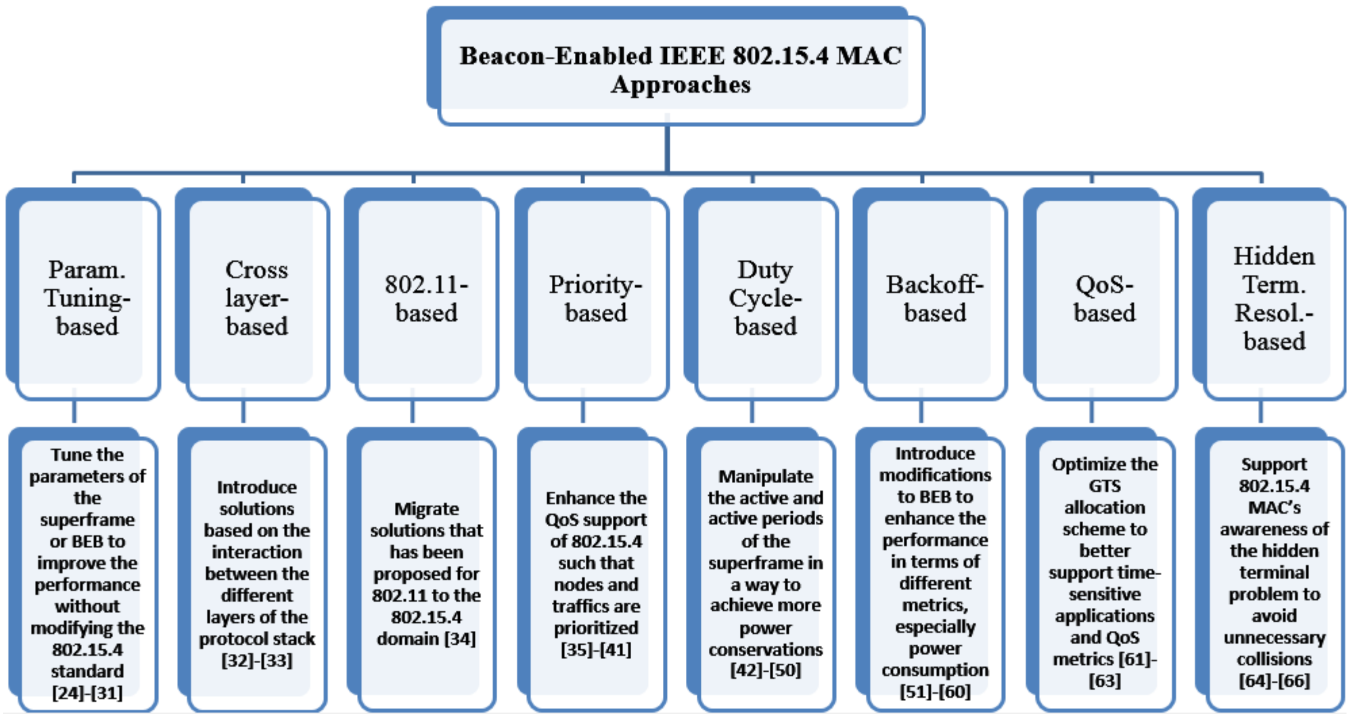

Fig. 3. Classification of approaches to improve the IEEE 802.15.4 MAC protocol.

beginning. After that, BO and SO for the cluster coordinator are computed before proceeding to computing them for the sensor nodes. The formulated equations to compute BO and SO guarantee that the PAN coordinator will get values different than those for the cluster coordinators. Also, the latter will have different values from those for the sensor nodes. Furthermore, SABTS utilizes offset times to adjust the starting times of sending beacons from the PAN coordinator and the coordinator nodes. SABTS is modeled using a Markov chain and its performance is compared to the standard 802.15.4. Simulation results show that SABTS outperforms the standard in terms of the probability of successful transmission, goodput, and energy consumption.

Casilari et al. in [29] propose policies to specify the Superframe Duration (SD) of clusters within an 802.15.4/ZigBee WSN. A time-division policy is assumed to specify how active part of the SD of neighbor coordinators is planned to be non-overlapping in time. This means that all superframes should be appropriately shifted a certain offset time. This policy imposes no changes to the specifications of 802.15.4. The authors assume the worst case scenario in which all of the coordinators have overlapping transmission ranges. As a result, a coordinator should not send its beacon during the superframe of any other coordinator. This leads to that the different superframes cannot overlap in time, and therefore, as one cluster is active the rest of the clusters must be in the inactive mode. The value of the BI is directly linked to the delay that a packet experiences as it travels from a cluster to another, and therefore, an upper bound is assumed on the value of BI. Based on all of these configurations, the authors devise diverse policies to define the value of the SD in a generic hierarchical cluster tree network. These policies include a policy that uses the same SO for all coordinators, a policy that considers an SO for the coordinator that is double the SO of its associated sensors, and a policy in which the coordinators SOs are made proportional to the traffic generated in the clusters. The performance of the network is studied under each of these policies. It is found that the third policy is capable of achieving the highest level of goodput in the network.

Yen et al. in [30] work on designing a probabilistic risk-aware beacon scheduling algorithm to achieve more efficient collision-free, beacon schedules. The authors criticize the traditional approach of having nodes schedule their beacons such that no reuse of beacon slots, among neighbors, results. They argue that this rule is too restrictive and slot reuse can still be exploited in a proper manner when the probability of collisions is rather low. The advantage of this approach is that reductions in packet delivery delays can be achieved. A node pair classification scheme is employed to identify pairs of nodes that are apart by at most two hops. This classification allows assessing how risky it is to reuse a slot by a pair of nodes. If the assessment reveals that the risk is high, slot reuse is avoided, and vice versa. After modeling the algorithm mathematically, simulations are conducted to study the performance of this new algorithm. Results show that, compared to several other algorithms, the new algorithm is capable of reducing the packet delivery delays significantly.

Neugebauer et al. in [31] propose the Beacon Order Adaptation Algorithm (BOAA) for controlling the value of BO in accordance with the communication frequency. BOAA is designed for WSNs with a star topology and is run by the star coordinator. The coordinator monitors the communication behavior of the surrounding sensor nodes and adaptively tunes the BO. With that, the coordinator will be able to prolong the networks lifetime by properly adjusting its duty cycle.

Once BOAA is invoked by the coordinator, the superframe is tuned with a low duty cycle in order not to miss sensors messages. That is, BO is set to zero at the beginning of the coordinators startup. The coordinator maintains a buffer matrix to record information about the communication frequency of each sensor in its star. Each row in the matrix corresponds to one superframe step while each column refers to a sensor node in the star network. The rows (that is, the superframe steps) associated with each node are the ones being tracked by the coordinator to learn about each nodes communication activity. BOAA works in cycles the number of which is equal to the number of superframe steps. Apparently, each step follows the pattern of the duty cycles due to the BI. Therefore, the time between two successive steps depends on the BO [31]. This way, the coordinator adjusts the BO and sends it to all respective sensor nodes. BOAA is mathematically modeled and simulated to check its performance. The results reveal that BOAA achieves power savings with a trade-off according to packet delivery delay.

B. Cross Layer-Based Approaches

Francesco et al. in [32] propose the ADaptive Access Parameters Tuning (ADAPT) algorithm, a cross-layer distributed framework for WSNs that implement the 802.15.4/ZigBee standards. The objective of ADAPT is to achieve a reliable and energy-efficient data communications in WSNs. Basically, the authors observe that different applications require different reliability levels, and therefore, they target improving the 802.15.4 MAC to obey that fact. Energy consumption, on the other hand, depends solely on the operating conditions of the network, which are very dynamic in nature. Therefore, conserving nodes energy requires a system that can adapt its parameters such that the lifetime of the network is prolonged. ADAPT employs an adaptation module that directly interacts with all the layers of the ZigBee stack. To facilitate the interaction, this module is realized as a vertical component that has direct access with each layer of the protocol stack. This architecture gives the adaptation module the ability to collect information from each layer and optimize the overall functionality of the node. Therefore, when the application layer specifies a targeted reliability, the adaptation module interacts with the MAC layer to tune its parameters, namely, macMinBE, macMaxCSMABackoffs, and macMaxFrameRetries, in a way that makes the desired reliability possible. The authors also address the main factors that affect the level of the reliability, namely, contention and channel errors, and incorporate two control schemes in ADAPT to mitigate their impact. Both control schemes tune the MAC parameters such that the reliability is confined to a certain predefined range. ADAPT is mathematically modelled and simulated for both single-hop and multiple-hop networks. The simulations show that ADAPT manages to outperform the standard in terms of delivery ratio and energy consumption per message.

Marco et al. in [33] introduce the Timely, Reliable, Energy-efficient and Dynamic (TREnD) cross-layer protocol for WSN-based control applications in industrial environments. The authors argue that concentrating on cross-layer approaches is more efficient in capturing and exploiting the complex interactions among the different protocol layers, which achieves a superior functionality. TREnD enables collaboration between the routing algorithm, MAC layer, and power control such that the desired reliability and latency are achieved. This is attained through an optimization process that is run with an objective to minimize the energy consumption. In TREnD, the routing mechanism is divided into static routing, to handle inter-cluster communications, and dynamic routing, to handle inter-node communications. The static routing is supported by a novel MAC protocol that follows a hybrid TDMA/CSMA approach. According to this MAC protocol, nodes wake up to transmit/receive only during the TDMA-slot associated to their cluster for transmitting/receiving, which reflects in more energy savings. The TDMA-cycle is organized in a way such that the different traffic patterns, for different cluster locations, are considered. Packets are exchanged between clusters. Nodes, within a transmitting cluster, with packets to send enter in the listening state. At the receiving cluster, each node multicasts a beacon message to all of the nodes in the transmitting cluster. A node that receives the beacon senses the channel and, once it finds the channel clear, unicasts its packet to the beacons sender. If no beacons are received, nodes at the transmitting cluster either keep on listening in the next CSMA-slot or enter the sleep mode. The sink node is the one responsible of setting the optimal parameters of operation (that is, the wake-up probability, the access probability, and the TDMA-slot duration), based on the available traffic and cluster topology, and communicating these parameters to the nodes in the network. Simulations show that TREnD performs effectively in terms of reliability, latency, duty cycling, and load balancing.

C. IEEE 802.11-Based Approaches

Minooei and Nojumi in [68] study the improvement of BEB in the context of IEEE 802.11. Lee et al. investigated the performance of that algorithm, which they call the Non-Overlapping BEB (NO-BEB), in the context of 802.15.4 networks [34]. NO-BEB modifies the way BEB selects the length of the contention window after an access failure. Basically, in order to reduce the level of contention over the medium, the contention window (W) is randomly selected from the range $[W_{i-1}, W_i]$ rather than $[0, W_i]$, where W_i is the contention window of the ith backoff stage [68]. This change guarantees that no overlapping with the previous range (that is, $[0, W_i]$) occurs. As a result, nodes experiencing different number of medium access failures have better chances of acquiring different contention windows from the non-overlapped regions. NO-BEB is modeled using Markov chain in [34] and shown to outperform BEB in terms of throughput, probability of collisions and average access delay.

D. Priority-Based Approaches

Shi et al. in [35] tackle the problem of real-time abnormal events monitoring and the need to distinguish between alarm signals and ordinary signals. They propose an improved CSMA-CA protocol based on Weighted-Fair-Queue (FQCSMA/CA) algorithm. This algorithm works on balancing the transmission quality among different signals based on their urgency, which is lacking in the 802.15.4 standard. Basically, FQ-CSMA/CA aims at guaranteeing reduced transmission delays for alarm signals, without compromising the transmission quality of ordinary signals. Towards that end, FQ-CSMA/CA uses weighted-fair-queuing to divide the nodes packets according to their priority. This means that weights are used to mark the different packets available in the queues of a node. A weight is the proportion of bandwidth assigned for a specific queue. This weight is explicitly specified within the data frame in the field priority-label. This weight is used by a classifier at each node to organize the nodes in the queues according to their priority. A packet scheduler will then select the packets with highest priority to service them first. The authors define five categories of signals, namely, sensor collected data, control command, ACK frame, system setting, and alarm signals, and state that alarm signals are given the largest weight (or priority), while the ACK frame is given the smallest one. The rest of the data are assigned equal weights. This categorization of data aims at achieving a level of fairness with which each type of data, except for the ACK frame, is given an equal opportunity of being transmitted provided that the alarm signals are sent first if they occur. Simulations show that FQ-CSMA/CA outperforms the 802.15.4 standard in term of the frame success probability. In particular, except for the ACK frames, FQ-CSMA/CA manages to deliver all the frames with probabilities better than 802.15.4. A similar observation can be seen with the average queue delay experienced by the different packets. With FQ-CSMA/CA, except for the ACK frames, all the frames have to wait for a period shorter than 802.15.4 before being serviced.

Ndih et al. in [36] observe that 802.15.4 offers a priority-independent functionality. This is resulting from having the nodes use the same contention access parameters. Therefore, the authors in develop a Markov-based analytical model for the CAP in which different sets of access parameters are permitted for the nodes with different priority classes. Two priority classes are recognized: high-priority (class 1) and low-priority (class 2). A node-state Markov-chain is developed for each priority class, beside a Markov-chain for the channel state. The priorities or service differentiation is based on assigning a contention window of 1 for class 1 nodes and 2 for class 2 nodes. Using these settings of the contention window, while maintaining the other backoff parameters at their standard-defined defaults, gives high-priority nodes higher opportunity to access the medium. This is because their small contention window size reduces the duration of their idle channel sensing.

Severino et al. in [37] work on differentiating traffic classes within the CAP such that differentiated services are offered to time-critical messages. Their approach is based on the proper tuning of the 802.15.4 MAC parameters macMinBE, macMaxBE, and W_{init} (the initial size of the contention window). The tuning depends on whether the frame is identified as a high-priority or not. Data frames are considered of low priority while command frames, like alarm reports and GTS requests, are considered of high priority. Therefore, nodes use different parameter settings depending on their traffic type. Similar to [36], the settings are chosen such that the backoff periods of high-priority frames are made shorter than those for the low-priority frames. Furthermore, while a queue of different frames is building up, a Priority Queuing is used such that higher-priority frames are selected first for transmission.

Jardosh et al. in [38] propose an explicit priority scheme for 802.15.4 MAC. According to this scheme, nodes are categorized into critical nodes and normal nodes. Critical nodes are the ones that have important information to send to the coordinator while normal nodes that send routine information, which can tolerate some delay. Critical nodes are considered of high-priority while normal nodes are considered of low-priority. The coordinator can learn about this categorization using a secondary beacon. Basically, critical nodes send the coordinator this beacon to indicate their high priority traffic. With that information, the coordinator restricts the contention during the CAP to only those critical nodes. That is, the coordinator includes the priority information in the primary beacon that it periodically broadcasts to all the nodes. Once notified, the normal nodes will refrain from attempting to access the medium during the CAP. This way, traffic priority is preserved and critical information is given preference over regular information.

Takaffoli et al. in [39] propose the GTS-TDMA algorithm which targets the improvement of GTS scheduling to recognize the nodes different priority classes. Under GTSTDMA, nodes do not request GTSs, GTSs are rather allocated to them using a GTS allocation scheme. The network is viewed as a multi-level tree and a TDMA schedule is constructed for it. The schedule is constructed such that maximum data rate is achieved for each node in the network. In other words, the TDMA-GTS algorithm seeks the optimal allocation of GTSs such that each node is provided with the maximum data rate it requires. Simulation results show that TDMA-GTS is capable of achieving almost twice the throughput of CSMA-CA. However, this algorithm exploits the GTS capability of 802.15.4 MAC and does not consider solving the priority problem during the CAP.

Kim and Kang in [40] tackle the problem of service differentiation in 802.15.4-based WSNs operating under non-saturation conditions. The authors propose two mechanisms, namely, the Contention Window Differentiation (CWD) mechanism and the Backoff Exponent Differentiation (BED) mechanism, with the objective of supporting a priority-based service differentiation scheme for WSNs. Under these mechanisms, nodes are grouped into different priority classes. Priorities are recognized according to the importance of the packets to be transmitted. For example, nodes that need high bandwidths and generate emergency data must have higher priorities than other nodes. Service differentiation is realized through the variation of the size of the contention window (with CWD) and the binary exponent (with BED). With CWD, nodes with different priorities are assigned different contention windows such that high-priority nodes experience short contention windows and vice versa. In the same manner, BED assigns different binary exponents to the different nodes priorities. Both BED and CWD apply a scheme known as the Backoff Counter Selection (BCS) that selects the next backoff period, after finding the medium busy during any CCA, from a shortened range (smaller than the range used in the 802.15.4 standard). The shortened range gives different nodes better chances of choosing different backoff periods. The benefits of that are the preservation of nodes priorities and the reduction in the probability of collision. The inclusion of the BCS scheme assists in accelerating the process of service differentiation. The authors develop Markov-based analytical models their new mechanisms. Simulations show that both CWD and BED are capable of prioritizing nodes according to the importance of their packets. However, it is shown that CWD and BED perform differently in terms of different performance metrics. Therefore, a guideline is presented to recommend the usage of CWD or BED depending on the desired performance.

Huang et al. in [41] propose the Adaptive GTS Allocation (AGA) scheme to support low latency and fairness. The idea of AGA is to provide an estimate of future GTS needs of the nodes. With that estimate, the coordinator gives higher priority of GTS allocation to needy nodes. AGA operates in a two-phase manner. In the first phase, nodes are classified according to their recent usage of GTSs and then assigned priority numbers (priority decreases as the priority number increases). In the second phase, GTSs are allocated with reference to the priority numbers such that nodes with low priority numbers are considered first. Although AGA shows promising results, over 802.15.4, in terms of fairness and low latency, the scheme, similar to GTS-TDMA above, concentrates on improving medium access during the CFP without considering the CAP.

E. Duty Cycle-Based Approaches

De Paz Alberola and Pesch in [42] propose the Duty Cycle Learning Algorithm (DCLA) to define how the nodes should be configured to achieve the optimal network performance under different traffic conditions. DCLA alleviates the need for human intervention and adapts the nodes duty cycles in a way to minimize power consumption while achieving superior performance in terms of successful data delivery. By running on the coordinator nodes, DCLA firstly gathers statistics from different nodes to estimate the incoming traffic load. Based on the gathered information, the Reinforcement Learning (RL) framework (see [69]) is used to decide on the duty cycle to use. Basically, RL depends on repetitive interactions, with the nodes, through which the selected duty cycle is updated iteratively till the best one, that achieves the targeted optimal performance, is hit. This way, DCLA can achieve a fully adaptive system that can self-correct its parameters based on the traffic conditions, without the need for any manual configurations that conform to specific requirements of different applications. This gives DCLA the credit of reducing time and cost of installation, operation and management. DCLA runs as a software on the coordinator nodes and requires low memory and processing capacities. Simulations show that DCLA, compared to other duty cycle adaptation schemes, is capable of achieving a superior performance in terms of energy efficiency, end-to-end delay, and probability of success.

Li et al. in [43] propose enhancements for the beacon-enabled mode in 802.15.4 MAC. The enhanced version of the standard, referred to as the Enhanced Beacon-Enabled Mode, aim at improving network performance and conserving more power for low data rate applications. The new mode is realized by two optional functions, namely, the Synchronized Low Power Listening (S-LPL) function and the Periodic Wakeup (PW) function. S-LPL helps in reducing the overhead of synchronization for low data rate applications, while PW, which is implemented during the inactive portion of the superframe, helps in reducing both transmission delays and packet loss rate. These two functions can be implemented in tandem or individually. The target of S-LPL is to improve the ability of nodes to save more power. Basically, the authors note that the 802.15.4 standard supports a BO of between 0 and 14. This is a relatively small range that constraints the ability of saving more power in low duty cycle applications. The standard does not support larger BOs for two reasons. First, with large BOs a node experiences synchronization overhead. That is, the node will spend more time to associate itself with a PAN coordinator. This extra time is accompanied with more depletion of the nodes power resources and the standard aims at avoiding that. Second, large BOs may cause synchronization difficulties because of the clock drift between nodes (see [43] for more details). With S-LPL longer synchronization periods are permitted for a portion of the nodes. These nodes receive the beacon less frequently (once every K beacons sent to the rest of the nodes). This means that these nodes will have to listen for extended periods of time before receiving the next beacon from the coordinator. Although this may lead to faster depletion of their power resources, S-LPL mitigates that by mandating that the coordinator should send a series of Virtual Preambles (VPs) to these nodes. The latter operate in a Low Power Listening (LPL) mode, which enables them to detect the VPs and synchronize their clocks with the coordinator. Under LPL, the nodes listening is on for a period of two VPs and off for a period of one VP. In this manner, nodes are able to conserve more power; and this reduces the effect of using longer synchronization periods. The authors show that the effect of sending the VPs on the power resources of the coordinator are minimal, provided that S-LPL is implemented for low data rate applications. PW, on the other hand, is introduced to handle the problem of delaying the data generated during the inactive period of the superframe. With PW, nodes with queued as well as newly generated data are permitted to send their data to the coordinator, which turns on its listening, during the inactive period. This behavior guarantees lower latency for these data. The coordinator, however, does not need to stay awake for the whole inactive duration; periodic sleeps, to compensate for the situations when the nodes are not sending anything, can still be implemented to reduce the coordinators loss of power. By coupling the PW capability with the aforementioned capability of enlarging BO, the anticipated transmission latency can be comparable to that achieved with the 802.15.4 standard. The Enhanced Beacon-Enabled Modes performance is studied through extensive simulations. These simulations show that the new mode can outperform the 802.15.4 standard in terms of the mean power consumption, the mean duty cycle, and the packet loss rate.

Gilani et al. in [44] introduce an adaptive CSMA/TDMA hybrid MAC protocol to improve the throughput and the energy consumption of the 802.15.4 MAC. The authors are motivated by the observation that CSMA-CA does not perform well under high traffic loads. Therefore, they propose to incorporate the concept of time division multiple access (TDMA) in the CAP of the superframe. In other words, a dynamic

TDMA period is incorporated into the CAP. The coordinator node is assigned the task of adaptively dividing the CAP into CSMA-CA slots and TDMA slots. The division is based on the state of the nodes queues and the level of collisions over the wireless medium. The state of the data queues can be known through reserved bits in the transmitted frames. Having the coordinator assign TDMA slots resolves the latters challenging problem of synchronization; the beacon frames that are sent periodically help in this direction. Also, since the targeted scenario in [44] is WSNs operating under heavy traffic loads, the use of a greedy algorithm to allocate TDMA slots can resolve the known issue with TDMA networks, namely, the underutilization of the communication channel. The main advantage of including TDMA slots in the CAP is that the number of nodes that take part in the contention is constrained. Therefore, lower collisions are anticipated, which reflects in improved throughput. Also, as nodes obey the TDMA concept, they refrain from contending for the medium and therefore their RF transmitters should be turned off. This is beneficial in reducing the energy expenditure of these nodes. These anticipations are confirmed through the simulations conducted by the authors. The simulations, however, show that the CSMA/TDMA hybrid protocol leads to increased end-to-end delays, compared to the 802.15.4 MAC, except when the superframe duration is set carefully. In other words, when long superframes are used, TDMA nodes have to wait longer before being able to send their packets, which contributes to increased delays.

Valero et al. in [45] propose DEEP, a MAC protocol for beacon-enabled 802.15.4 that optimizes the distribution of the guaranteed time slots (GTSs) such that better energy conservation is achieved. In particular, instead of having a GTS descriptor (that defines the nodes address as well as the GTS slot and direct) available in all subsequent beacons till the node requests its de-allocation, DEEP removes the GTS descriptor from the beacon once the associated node acknowledges its reception. Indeed, nodes that do not support DEEP can still follow the 802.15.4 standard in keeping the unacknowledged GTS descriptor in all beacons. This makes DEEP backward compatible. DEEP can effectively reduce the size of the communicated beacons and thus the power consumed to process them at the receiving nodes is significantly reduced. Gadallah and Jaafari in [46] propose enhancements for the non-beaconed 802.15.4. Their enhancements target energy efficiency as well as reliable delivery of critical traffic. Basically, during network initialization, the duty cycle of the nodes is divided into active and inactive periods. During the active periods, nodes contend to access the medium according to the unslotted CSMA scheme. However, nodes sleep during the inactive periods. Nodes remain in the active mode while delivering critical data traffics. This behavior achieves higher reliability. However, inactive nodes allow nodes to conserve more power than the case is in the original non-beaconed 802.15.4, in which nodes are always awake and contending to access the medium. While this proposal outperforms the 802.15.4 standard as per the aforementioned parameters, it requires the employment of a synchronization scheme in the non-beaconed mode of 802.15.4. The overhead associated with that is not addressed in [46].

Bhatti et al. in [47] propose modifications to beacon-enabled 802.15.4 to improve its performance in terms of latency and reliability, and therefore, make it conform to the requirements of industrial applications. Towards that, the authors propose three schemes 1) swap the positions of CAP and CFP in the superframe and allow failed GTS frames to be retransmitted in during the CAP, 2) in the original 802.15.4 MAC, allow the retransmission of GTS frames in the CAP of the following superframe, and 3) in the original 802.15.4 MAC, allow the retransmission of GTS frames in the CAP of the current frame. Through a simulation study, the authors point out the gains they can achieve with their modifications over the original 802.15.4 MAC.

Ramachandran et al. in [48] present a thorough study and modeling of 802.15.4 MAC based on Markov chain. Their aim is to examine the performance in terms of throughput and energy consumption. The developed Markov-based model observes some approximations, In particular, the CSMA algorithm is assumed to be non-persistent. Also, in computing the probability of finding the channel busy during a specific time slot or the probability of sending a packet in a specific time slot, the steady-state probabilities are used to simplify the calculations. Finally, instead of selecting the next backoff period, after sensing the channel busy, based on a uniform distribution, it is assumed that a geometric distribution is used. The objective of this study is to understand the effect of shutting nodes down while no packets are available for transmission. After that, a modification to the specification of 802.15.4 MAC, in terms of the initialization of the contention window, is proposed to improve the performance.

Kouba et al. in [49] propose the Time Division Beacon Scheduling (TDBS) mechanism to mitigate the beacon frame collision problem in cluster-tree WSNs. With this problem, beacon frames collide due to having two or more coordinators either in the transmission range of each other, or communicating with overlapping transmission ranges. To resolve this situation, which is directly related to the synchronization problem, the authors present the TDBS mechanism in which the superframe duration scheduling (SDS) algorithm employed. In SDS, avoiding beacons collision depends on finding a cyclic schedule for the SDs such that at least one SD is accommodated in each BI. Also, the distance between any two consecutive SDs must be equal to BI. These rules guarantee that no overlapping can occur among beacon transmissions. SDS is also coupled with an efficient duty cycle management mechanism that distributes the bandwidth resources in a fair manner. This mechanism allocates bandwidth to the coordinators, based on their traffic needs, using an optimization formulation. This formulation defines a set of linear equations that describe the network constraints associated with the duty cycle of each coordinator and its relation to other coordinators duty cycles. These constraints, like having the sum of all duty-cycles to be one at most, depend on the metric being optimized (duty cycle in our case) and can be easily modified to optimize other metrics (like delay, buffer size$\cdots$etc). Finally, the feasibility of the TDBS mechanism is demonstrated through implementation in an experimental test-bed.

Muthukumaran et al. in [50] propose MeshMAC, a distributed beacon scheduling mechanism that enables the

802.15.4 standard to support peer-to-peer WSNs in the low-power, beacon-enabled mode. Basically, MeshMAC assumes that the whole network operates on the same BI and SD (the values of which are defined by the standard). To allocate a schedule for a node, the sum of the duty cycles of its 2-hop neighbors should be one at most. MeshMAC reserves one active SD exclusively for broadcast communication. Each node educates itself with the time slots that are already occupied by all other nodes in its 2-hop transmission range. Based on that knowledge, a node selects the first empty time slot it encounters and then broadcasts its selection to the other nodes. Two types of data transmission are supported by MeshMAC, namely, broadcast and unicast. Broadcast happens during the aforementioned reserved time slot. This slot is used for synchronizing the nodes. The unicast transmission happens during the active period of a destination node. The major benefit of MeshMAC is that nodes prepare their schedules in a distributed manner (that is, each node uses its local information about its 2-hop neighbors) that requires no intervention from a coordinator node. The evaluation of MeshMAC shows that it can perform in an energy-efficient, scalable fashion compared to the 802.15.4 MAC.

F. Backoff-Based Approaches

Wang et al. in [51] provide a comprehensive performance analysis of the CAP in the 802.15.4 MAC protocol. Both node states and channel states models are developed based on Markov chain. The authors demonstrate that these models can accurately match the functionality of 802.15.4 MAC during the CAP. Based on these models, it is proven that the standard performs poorly in terms of the achieved throughput. The authors discuss that this degradation in the performance is due to the inappropriate length of the backoff slot, which is set to aUnitBackoffPeriod in the standard. This length is relatively big and reduces the points at which nodes are allowed to compete for medium access, and therefore, this reflects into higher probabilities of collisions. Motivated by this discussion, the authors propose a modification to the superframe CAP. In this modification, the standard duration of the backoff slot is divided evenly into multiple smaller slots. This means that the number of the starting points at which the nodes contend to access the medium are increased; this provides better opportunities for accessing the medium. This change in the CAP is not accompanied with any modifications to the CSMA-CA algorithm itself. New node/channel states models are developed to capture the new changes to and a performance comparison is held with the original CSMA-CA algorithm. Simulations show that the changes are showing significant improvement in the achieved throughput (which is a result of reducing packet collisions). To more enhance the performance of the CSMA-CA algorithm, a new backoff mechanism is proposed in which a new time unit is used along with a relatively large range to randomly select the backoff periods from. The definition of the new time unit is inspired by the aforementioned division of aUnitBackoffPeriod into smaller slots. On the other hand, the wider range to select the backoff periods from is introduced to guarantee that the number of nodes contending to access the medium is reduced, which reflects in a reduced probability of collisions. Finally, the study in [51] is supported with additional simulations to examine the performance of these modifications. The results show that the proposed enhancements to CSMA-CA can significantly improve the throughput, reduce the end-to-end delay, and increase the rate of packet delivery success.

Mori et al. in [52] propose a distributed backoff mechanism to enhance the transmission performance of 802.15.4 MAC in cluster-based WSNs. The authors highlight the problem of channel access congestion that appears among the nodes that did not have enough time to send their packets during the last CAP. These nodes will commence their packet transmission, concurrently, at the beginning of the next CAP. This leads to higher incidents of collisions, and therefore, degrades the transmission performance. To mitigate this consequence, the authors propose that the nodes are required, at the beginning of the next CAP, to start their backoff periods at different time instants within the range of CAP. This is coupled with the fact that nodes should use a constant BE, set to the default macMinBE. The distinct starting points of the backoffs are randomly selected by each node from a Distribution Window (DW). The length of DW can be either constant (CDW) or adaptive (ADW). ADW is adapted in accordance to the traffic load experienced in the cluster. That is, DW shrinks with light traffic loads and expands otherwise. The coordinator of the cluster is responsible of informing the nodes about the heaviness of the traffic load. The authors provide a simulation study to examine the performance of this new backoff mechanism in terms of throughput and transmission delay. It is shown that the throughput of the new mechanism is directly affected by the lengths of the DW. The proper setting of DW can guarantee a throughput that is comparable to the conventional 802.15.4 MAC. However, the effectiveness of the new mechanism appears in its ability to outperform the 802.15.4 MAC protocol in terms of the reduction in the transmission delay under heavy traffic load. Again, the setting of DW greatly affects the latter performance.

Zhu et al. in [53] introduce the Linear Increase Backoff (LIB), a modified CSMA-CA mechanism to better serve time-critical applications. LIB targets enhancing the performance in terms of packet delay without affecting the energy efficiency and the throughput. The main change introduced by LIB is that backoff counters increase linearly, instead of exponentially, when either of the two CCAs reveals that the channel is busy. This change is motivated by the fact that the exponential increase in the backoff counter may force certain nodes to wait for an extended period of time before being able to commence its CCAs. This allows other nodes, with relatively shorter backoff periods, to capture the medium more frequently. The linear increase in the backoff counter, however, can guarantee to keep the backoff periods at reasonable lengths that allow nodes to gain a fair access to the medium. LIB also requires other changes to the standard CSMA-CA algorithm. It mandates that if a packet cannot be sent within a superframe, it should be dropped and not deferred to the next superframe. Also, nodes should be in the sleep mode, rather than the receiving-idle mode, during the backoff states, at the end of a successful transmission, when crossing the retries limit, and when crossing the maximum number of backoff stages.

Furthermore, LIB assumes that the redundancy in the deployed sensor nodes can obviate the need for using ACK packets. A comprehensive Markov-based model is developed for LIB to analyze its characteristics. Simulations show that LIB is effective in achieving a considerable reduction in the delay. Also, for large network sizes and high traffic intensity, LIB shows promising results in terms of improving the throughput and reducing the energy consumption.

Jing et al. in [54] tackle the problem of maximizing the throughput of the 802.15.4 standard through a new adaptive backoff mechanism. The authors use nonlinear programming (NLP) to optimize the throughput in the network, considering a certain network size and the data payload. Based on the results of the optimization problem, the backoff mechanism is designed using an approximate Markov model. In this backoff mechanism, after finding the medium busy at a certain backoff stage, the node dos not choose its next backoff period based on a uniform probability (as the case is with 802.15.4 MAC). Instead, the next backoff period is chosen based on a probability that controls the length of this period depending on the networks size. Therefore, as the network size increases, backoff periods are chosen large such that the contention to access the medium is reduced. Simulations have been conducted and showed that the new backoff mechanism outperforms 802.15.4 MAC in terms of throughput and the probability of successful transmission. Khan et al. in [55] introduce the Improved BEB (IBEB) algorithm. In IBEB each node, after specifying its BE, randomly selects an Interim Backoff (IB), which is restricted to be 10% to 40% of the specified backoff delay. The authors argue that this approach tends to reduce packet collisions since the probability of having two nodes randomly selecting the same BE and IB is quite low. The authors provided a simulation study to examine IBEBs performance in terms of latency, channel utilization, goodput, and average number of collisions. The results showed that IBEB outperforms BEB in terms of these parameters.

Wong and Hsu in [56] introduce the Additional Carrier Sensing (ACS) algorithm to enhance the performance of CSMA-CA. ACS is designed specifically for WSNs operating under acknowledged traffic conditions. The authors highlight the fact that the wireless medium can be busy during the CCA2 due to two reasons. First, when a nodes CCA1 coincides with another nodes CCA2. In this case, the latter node commences its packet transmission during the former nodes CCA2. Second, when a node initiates its CCA1 while another node waits for the ACK packet. In this case, the latter node receives its ACK during the former nodes CCA2. The ACS algorithm exploits the latter situation by allowing the node with the failing CCA2 to conduct an additional CCA (referred to as CCA3). In this case, there is a chance that the medium becomes idle after the ACK packet has been delivered. Therefore, the node initiating CCA3 has an opportunity to find the medium idle, which allows it to send its packet thereafter. This behavior saves the node the need to experience another backoff period, which is anticipated to result in enhanced performance. ACS has been mathematically modelled, using Markov chain, and simulated to study its performance. The collected results show that ACS is superior to the standard CSMA-CA in terms of the achieved throughput and delay. Also, the number of CCAs used by a node before sending a packet is found to be less with ACS. This implies that ACS loses less power during CCAs.

Royo et al. in [57] propose the 2-Cell with Sorted wait for WSNs (2CS-WSN) algorithm to resolve conflicts among nodes contending to access the medium. 2CS-WSN is a collision resolution mechanism by which nodes that suffered from a collision during a certain time slot will start a procedure to resolve their conflict in the next time slot. The procedure ends once all of the collided nodes manage to send their packets. With 2CS-WSN starts operating after the ordinary, standard two CCAs have been conducted. Once a collision occurs, nodes will be grouped into two cells, namely, the Transmission Cell (TC) and the Waiting Cell (WC). TC includes the nodes that randomly choose to retry their transmission attempts, while *WC* contains the nodes that randomly choose to defer their packet transmissions. Next, TC's nodes retry their transmissions at the same time, which results in another collision. This forces some of these nodes to form a new *WC*, called WC_1, while the old WC is renamed as WC_2. The TC keeps on shrinking, and *WCs* keep on forming, until one node remains in the TC. The latter node ends up successful in transmitting its packet. After that WC_1's nodes move to TC and the nodes in any WC_{i+1} move to the next WC_i. This procedure is repeated until all of the nodes that experienced the aforementioned collision mange to send their packets. Simulations are run to study the performance of 2CS-WSN against the standard CSMA-CA. In terms of throughput, 2CS-WSN manages to outperform CSMA-CA significantly. Furthermore, although the mean packet delay increases highly with 2CS-WSN, the algorithm tolerates that for the sake of reducing the rate of packet loss. In terms of the time as well as the number of retries needed to resolve a collision; it is found that 2CS-WSN reduces these metrics effectively when the number of colliding nodes increases.

Yedvalli and Krishnamachari in [58] propose enhancements to the 802.15.4 MAC protocol in dense sensor WSNs. The authors are motivated by the protocols poor performance in terms of throughput and energy consumption as the number of transmitting nodes increase in the network. In their solution, they firstly model the 802.15.4 MAC protocol as a p-persistent CSMA with changing transmission probability. From this model they extract the optimal transmission probabilities with which throughput and energy conservation are maximized. It is noted that when the optimal probabilities are used, the ratio of the idle time between successful transmissions to the delay between them is constant. Furthermore, this ratio tends to increase as the transmission probability gets below the optimal probability and vice versa. Based on this observation, the authors develop an enhanced 802.15.4 MAC protocol that uses distributed channel feedback-based mechanism to tune the transmission probabilities dynamically towards the optimal values. Basically, the standard backoff mechanism is changed as follows. First, the update of the backoff windows size is made after successful transmissions, rather than collisions or busy CCAs. Second, under saturated traffic, the window sizes should be consistent with the size of the network. Third, under unsaturated traffic, the window sizes should decrease following every successful transmission as the optimal probability increases. In brief, the new enhanced protocol modifies the standard only in terms of when and how the backoff window is updated. Simulations show that the enhanced protocol manages to outperform the standard in terms of the achieved throughput and the consumed energy.

Woo et al. in [59] propose the Knowledge-based Exponential Backoff (KEB) algorithm. The main target of KEB is to improve the throughput depending on the channel state information as collected by each node. Each node uses the Exponential Weighted Moving Average (EWMA), with a smoothing factor , to compute locally the collision rate after each successful transmission. Based on that computation, the value of BE is adjusted to achieve higher throughput. In other words, as the collision rate increases beyond a predefined collision threshold , BE will be increased and thus nodes backoff for longer periods of time (in order to reduce the level of communications over the medium, which reduces the collisions). In contrast, as the collision rate remains below , nodes backoff for shorter periods of time, which improves the utilization of the communication channel. KEB has been modeled using Markov chain and then simulated to validate the analytical model. The provided results show that KEB outperforms BEB in terms of throughput. The authors also provide a simulation study to find out the optimal values of the smoothing factor and the collision threshold that achieve the best throughput performance.

Ha et al. in [60] propose two mechanisms to improve the performance of CSMA-CA algorithm in 802.15.4 terms of throughput and energy efficiency. These mechanisms are the Enhanced Collision Resolution (ECR) and the Enhanced Backoff (EB) mechanisms. The ECR mechanism changes the standards approach in updating the value of BE. The authors notice that a pair of CCAs is not enough to indicate the level of contention. Therefore, with ECR the value of BE is not increased until a fixed number of consecutive CCAs are found busy. This fixed number is set to macMaxCSMABackoffs. Also, rather than resetting BE to its minimum value after a transmission (as in the standard), BEs value is adjusted based on the result of the packet transmission. If the transmission fails, it indicates high channel contention and thus BE is increased. If transmission succeeds, BE is decreased. This approach guarantees that BE is decreased slowly, and therefore, the information about the level of contention over the channel is preserved. Being aware of the status of the communication channel has a direct positive effect on the behavior of the CSMA-CA algorithm and it can enhance the overall performance of 802.15.4 MAC. On the other hand, the EB mechanism works on avoiding overlaps among different backoffs and CCAs, for different nodes, by shifting the range of backoff counters. The shift is based on an estimate of the expected number of busy backoff periods to follow (the details of how this estimate is computed can be found in [60]). Both ECR and EB mechanisms are evaluated in terms of throughput and energy efficiency (ratio of throughput and energy consumption). The provided simulations show that under saturated traffic conditions, ECR is superior to the 802.15.4 MAC protocol in terms of both performance metrics. Moreover, combining both ECR and EB can provide further improvements over 802.15.4 MAC. With unsaturated traffic conditions, the same improvements are observed only as the number of nodes increase in the network.

G. QoS-Based Approaches

Koubaa et al. in [61] propose the Implicit GTS Allocation Mechanism (i-GAME) to overcome the limitations associated with the GTS allocation mechanism in beacon-enabled IEEE 802.15.4. With i-GAME, instead of assigning a single GTS to a requesting node, multiple nodes will be sharing the same GTS, provided that the PAN coordinator can form a schedule that fits the requirements of those sharing nodes. This means that, in contrast to the standard, different nodes will be benefiting, in a dynamic manner, from the time slots of the shared GTS in each superframe. i-GAME operation depends on the traffic specification and the delay requirements of the requesting nodes as well as the available GTS resources. Nodes will no more request a fixed number of time slots. Instead, they send their traffic specification and delay requirements to the coordinator. The coordinator uses this information to run an admission control algorithm that evaluates the available GTS resources and responds in accordance. Requests will be accepted if the coordinator can create a schedule that satisfies their requirements; otherwise, the requests will be rejected. The authors provide mathematical modeling and simulations to study the performance of i-GAME. Their results show that i-GAME, compared to the standard GTS allocation, is capable of improving the performance in terms of bandwidth utilization efficiency.

Shrestha et al. in [62] propose a GTS allocation scheme that aims at improving reliability and bandwidth utilization in Wireless Body Area Sensor Networks. The scheme is based on an optimization problem with an objective to minimize the bandwidth requirement. The authors criticize the standards approach to allocating GTSs based on a first-come-first-serve basis. This approach leads to wastes in bandwidth due to failing in accommodating the asymmetric traffic emanating from different sensor nodes. To mitigate this problem, the authors define a priority measure that depends on the nodes packet generation rates. Nodes are required to check their buffers to see if they have a number of packets that is larger than a defined threshold. This step helps the nodes to set their priorities. They include the latter information in their GTS allocation requests to the coordinator. The coordinator collects these requests during the CAP period and then solves a fractional knapsack optimization problem to better allocate GTSs according to nodes priorities. The proposed algorithm requires no modifications to the specifications of 802.15.4. After providing their mathematical formulation, the authors studied the performance of their algorithm through simulations. Their results show that their algorithm outperforms the standard GTS allocation scheme in terms of many metrics like the average packet delivery ratio, delay, and packet discard rate.

Na et al. in [63] design the GTS Scheduling Algorithm (GSA), an optimal GTS scheduling algorithm to meet the delay bounds of time-sensitive applications like wireless video surveillance and target detection. GSA assumes a WSN with a star topology. A node that is initiating a time-sensitive transaction (T) should specify the time-constraint and the total payload it requires to complete that transaction. This information should be sent to the coordinator as part of the GTS request. The coordinator evaluates the request based on the number of GTSs needed by the payload and how these GTSs will be arranged to meet the time deadline. These requirements are checked over three steps. Firstly, the coordinator checks if it is possible to add a new T to the schedule without affecting the already scheduled transactions. If this step is successful, then, the coordinator moves to estimating the delay to be experienced in serving T. Also, the coordinator analyses how that delay will affect the number of GTSs allocated to T in each beacon interval. Finally, based on the latter analysis, GSA assigns the minimum number of GTSs to T in each beacon interval, which maximally spreads out Ts payload. GSA ensures that GTSs are utilized in an optimal manner by adjusting the assignments of GTSs whenever changes occur in the payloads transmitted in a CFP. GSA spreads out the GTSs evenly over multiple beacon intervals to have a smooth traffic flow between the coordinator and the nodes. The performance of GSA is studied under bursty, periodic, and aperiodic transmissions. The results show that GSA outperforms the standard GTS allocation scheme in terms of the time constraint meet ratio, maximum time constraint violation, transaction abort ratio, and GTS utilization.

H. Hidden Terminal Resolution-Based Approaches

Tseng et al. in [64] propose the Cross-Layer DetectioN and Allocation (CL-DNA) scheme to address the hidden terminal problem in 802.15.4-based WSNs. CL-DNA does not introduce any extra control overhead in data transmissions. CL-DNA depends on operations in both the PHY layer and the MAC sub-layer as follows. Once a packet collision occurs, the PHY layer detects the addresses of the involved nodes from the collided signals. Detection of the node addresses is accomplished by depending on the Energy Detection (ED) feature of 802.15.4, see [61] and [4] for more details. This way, the hidden nodes can be identified. Then, the MAC layer performs another check on the addresses of the hidden terminals, using an address verification procedure, and adds the confirmed addresses to a hidden device address list (HDAL). The HDAL is useful in preparing non-overlapping schedules for the hidden terminals such that the chance of collisions id highly minimized. A detailed mathematical model is provided for CL-DNA and simulations are conducted to examine its performance. It is found that CL-DNA, compared to the standard, is able to achieve promising behavior in terms of goodput, MAC delay, and power consumption.

Koubaa et al. in [65] introduce the H-NAMe, a hidden terminal avoidance mechanism for clustered WSNs. H-NAMe employs grouping strategies that separates nodes a way to avoid overlapping regions of transmissions. At the intracluster level, the authors define a grouping strategy that splits the nodes into groups that have distinct time windows for their communications during the CAP. This grouping guarantees that nodes belonging to different groups can transmit without facing hidden terminal collisions. However, this strategy cannot guarantee that nodes in adjacent clusters will not be causing the hidden terminal problem. Therefore, to avoid the intercluster hidden terminal situation we need an intercluster grouping strategy. The latter refers to defining distinct groups of clusters whose nodes are allowed to communicate during the same time window. The performance of H-NAMe is evaluated though an experimental test-bed. The provided results show that H-NAMe can effectively outperform the standard in terms of the throughput, energy consumption, and probability of success.

Sheu et al. in [66] devise the Carrier Sense Multiple Access with Collision Freeze (CSMA/CF) protocol, a new multiple access protocol that employs both a collision resolution as well as a P-frozen contention strategies. The collision resolution scheme (CRS) is used to recognize the collided node and inhibit any two anterior collided nodes from experiencing more collisions. CRS is based on the technique in [67] that can recover data from collided signals, and therefore, identify the addresses of the collided nodes. When a collision occurs, CRS can recover two fields from the 802.15.4 MAC frame, namely, the frame length (FL) and the source address (SA). This way, the collided nodes are recognized. The coordinator moves these nodes from CAP to CFP (using GTS) in the next superframe. This behavior has a significant role in reducing collisions. However, in order to avoid having a growing number of nodes moving to the CFP, which may waste the CAP, the P-frozen contention strategy (PFCS) is employed. PFCS monitors the retry counter at these nodes and based on a predefined threshold it decides whether the node should be allowed to contend during the CAP or be moved to the CFP. The authors provide a mathematical modeling for CSMA/CF and study its behavior through simulations. Their results show that CSMA/CF can achieve promising performance in terms of energy conservation, access delay, and reliability. In Table II we highlight the strengths and weaknesses of all the categories of approaches we discussed in this paper.

V. Conclusion and Remarks

The research contributions that we have reviewed in this paper reveal the criticality of the 802.15.4 standard and the importance of improving it to support a diverse field of applications. We have highlighted the problem of coexistence with which an 802.15.4-based Wireless Sensor Network (WSN) is collocated with other wireless networks (like WLAN and Bluetooth) that operate in the 2.4 GHz-ISM band. Such collocation results in interference and can lead to serious disruption in the operation of the WSN. We have described some of the available solutions to resolve the coexistence problem and highlighted their strengths and weaknesses. Based on the review and discussions that we have delved in, we can state that devising new enhancements to the 802.15.4 standard should conform to the following specifications:

1) Distributed solutions: given the huge size of WSNs and the scarce power resources of the sensor nodes, distributed solutions are preferred over centralized ones. Distributed solutions can effectively support scalability and simplify the deployment/elimination of sensor nodes.
2) Adaptive solutions: given the self-organizing nature of WSNs, sensor nodes should have high ability to change

TABLE II
COMPARISON OF IEEE 802.15.4 MAC APPROACHES

Category of Approaches	Strengths	Weaknesses
Parameter Tuning-based	• No modifications to 802.15.4	• Application Specific • Performance bounded by the theoretical ranges of MAC parameters
Cross Layer-based	• Optimized performance by involving the perspective of different layers	• Control overhead to support interlevel interaction • Increases in latency
802.11-based	• Reuse of tested technology	• Designed with no special measures to conserve power
Priority-based	• Support QoS requirements during the CAP	• Overhead of classifying nodes and traffic is accompanied by extra power expenditures
Duty Cycle-based	• Exploit 802.15.4 capabilities with minimum modifications to it • Discover more opportunities to conserve power using original design of the standard	• Burden the PAN coordinator with an overhead of processing and analysis
Backoff-based	• Make 802.15.4 MAC more adaptive and dynamic • Support network scalability • Fit different topologies • May require no hardware upgrades	• May introduce major changes to the standard • Being adaptive comes at the expense of extra processing tasks at each sensor node
QoS-based	• Enhance the GTS feature of 802.15.4 • Better support for time-sensitive applications	• Impose extra tasks on PAN coordinators to solve complicated optimization problems
Hidden Terminal Resolution-based	• Significant reduction in collisions • Eliminate unnecessary packet retransmissions • Better utilization of power resources	• Overhead on the PAN coordinator to apply a suitable node grouping strategy to avoid overlaps of transmissions

their local parameters and adapt them to different conditions in the network. These conditions include the level of collisions over the wireless medium, traffic urgency, number of medium access failures, size of the networketc.

3) Power-efficient solutions: conserving the power resources of sensor nodes is a stringent requirement that cannot be undermined. Complex solutions that burden the sensor platform with additional power-consuming tasks are not favored in WSNs.
4) 802.15.4-centerd solutions: aside from the drawbacks of 802.15.4, its design abides by the general characteristics of WSNs and we need to build new solutions on top of it. That is, modifications to this standard should not change its core functionality. Rather, we need to focus on exploiting the strengths of this standard to mitigate its limitations (for example, how to benefit from the innovative idea of CCAs to achieve more power savings).

From another side, as a future work, it is important to highlight that a general look at the MAC categorization we have provided reveals the possibility of merging the objectives of two categories into one protocol. For example, it is an interesting research to study the impact of combining Parameter Tuning-based protocols with QoS-based ones. Such a study can reveal the consequences of intelligently modifying the parameters of the 802.15.4 standard as well as exploiting its GTS feature in order to achieve performance improvements on different levels. Also, Coexistence Resolution-based approaches can benefit from the Hidden Terminal Resolution-based ones, and vice versa, to improve nodes awareness of the availability of other nodes (may be supporting different technologies other than 802.15.4). Moreover, Priority-based approaches can be combined with QoS-based ones to give better support for a diverse set of applications with different service requirements. This is because such a combination may exploit both the CAP and GTS features of the superframe to support different types of services and applications in various fields. We can also notice that some techniques used to manage duty cycles (in Duty Cycle-based approaches) may be useful in resolving the coexistence problem because many Coexistence Resolution-based approaches depend on manipulating the superframe structure and timing.

Another worth noting point is that little attention has been given to exploiting the Clear Channel Assessment (CCA) feature of 802.15.4. Few works have observed that the use of two CCAs may be leading to unnecessary waste of resources. We see that some important enhancements to 802.15.4 can be achieved through modifying the way CCAs are designed. For example, it will be interesting to study the impact of increasing the number of CCAs for certain nodes. These nodes may need priority to access the wireless medium due to the importance of the traffic they intend to transmit; the increase in the number of CCAs saves them the delay they may encounter by backing off repeatedly. Such an arrangement may pave the way for a better support for QoS parameters. This approach may be further refined by changing the number of CCAs based on the size of the network and the intensity of the traffic.

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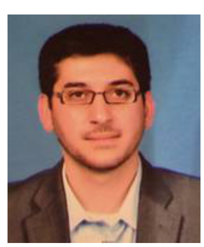

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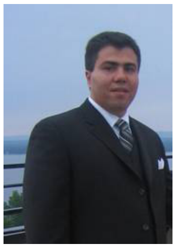

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