Egyptian Informatics Journal 24 (2023) 100410

Contents lists available at ScienceDirect

Egyptian Informatics Journal

journal homepage: www.sciencedirect.com

Review

Contention-based traffic priority MAC protocols in wireless body area networks: A thematic review

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ARTICLE INFO

Keywords:
Wireless Body Area Networks (WBANs)
MAC protocols
Traffic classification
Traffic prioritization
Contention-based Prioritization
slotted-CSMA/CA

ABSTRACT

Wireless Body Area Networks (WBANs) healthcare application is a group of heterogeneous-natured Bio-Medical Sensor Nodes (BMSNs) used to sense and monitor a patient's vital signs, in the long run, under natural physiological conditions, without affecting the regular activities. Heterogeneous-natured BMSNs demand prioritized channel access during contention access phases to transmit data or allocate time slots in contention-free phases. Thus, contention-based prioritization of heterogeneous traffic is required in WBANs. Therefore, many researchers have considered and presented various traffic-priority Medium Access Control (MAC) protocols. This paper provides a thematic review of contention-based traffic priority MAC protocols in WBANs. Slotted Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) scheme in beacon-enabled modes of IEEE 802.15.4 and IEEE 802.15.6 MACs is also analyzed regarding contention-based traffic prioritization. In addition, a critical and comparative analysis of existing contention-based traffic priority MAC protocols is obtained. A hierarchy of contention-based traffic priority MAC protocols is proposed. This review on contention-based traffic priority MAC protocols in WBANs extends the body of knowledge. This paper, therefore, serves as the first and enhances the concept of contention-based traffic prioritization at the MAC layer in WBANs. We have confidence that this paper will stimulate a better way of solving the contention-based traffic prioritization problem.

1. Introduction

Wireless Body Area Networks (WBANs) provide real-time, unsupervised, and non-stop health monitoring; thus, reducing healthcare costs. In addition, WBANs proactively manage and early diagnose various human diseases. WBANs are also used in different applications. WBAN applications comprise patient's vital-signs monitoring, non-stop and long-term health monitoring, and monitoring workers employed in life-critical areas such as war fields, deep-sea, space, etc. [1]. Moreover, WBANs are also applied in sports [2,3], entertainment [4,5], Military [6,7], driving assistance [8], security [9,10], and E-billing payment [11,12].

WBAN is a group of smart, lightweight, and low battery power heterogeneous-natured Bio-Medical Sensor Nodes (BMSNs) positioned over or inside the patient's body or fabricated in cloths [13–17]. These BMSNs have diverse computational power, storage capacity, and data generation rate [18–24]. The heterogeneous-natured BMSNs such as blood pressure, body temperature, respiratory rate monitors, motion sensing, Electrocardiography (ECG), Electroencephalography (EEG), Electromyography (EMG), pH-level monitors, heart rate, and others are deployed to observe humans vital-signs information. BMSNs transmit the observed human vital-signs information to Body Coordinator (BC) via intra-WBANs as depicted in Fig. 1. These BMSNs generate real-time feedback [23].

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https://doi.org/10.1016/j.eij.2023.100410
Received 22 March 2023; Received in revised form 21 July 2023; Accepted 28 September 2023
Available online 15 October 2023
1110-8665/

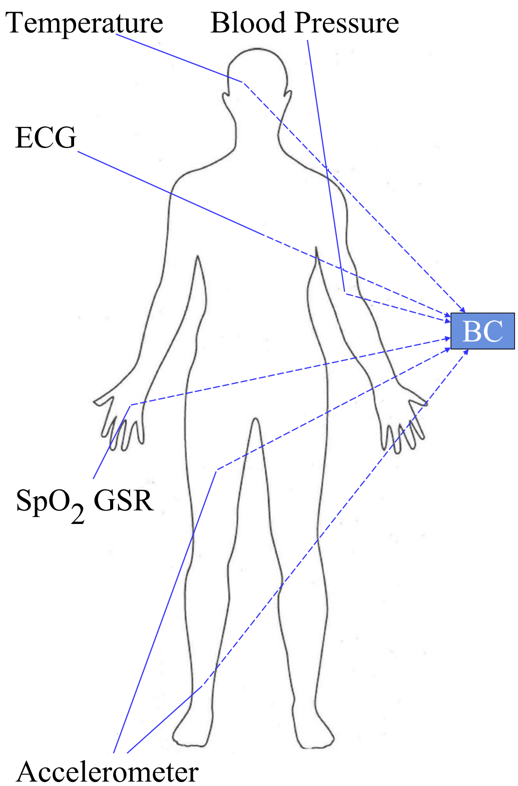

Fig. 1. Intra-WBAN communication architecture.

Heterogeneous-natured BMSNs produce a variety of data packets containing vital-signs information. Some data packets can bear little losses but are delay-sensitive, while others cannot tolerate losses and are also delay-sensitive. Besides, several data packets require delivery with minimum or no loss without any time constraint, whereas others do not have such constraints. Thus, prioritized channel access is necessary [25–29]. Also, WBAN must fulfil diverse requirements of simultaneously executable healthcare applications [26,30–34]. WBANs have low bandwidth, short broadcasting range, insufficient storage capacity, and limited computational power [35–40].

BMSNs access the shared medium in collaboration with Medium Access Control (MAC). The MAC plays a key role in enhancing the overall network performance [41]. MAC is the most suitable layer for reducing Packet Delivery Delay (PDD) and energy consumption [42–51]. Therefore, numerous energy-efficient MAC protocols such as [22,52–67] have been proposed. Several MAC protocols are proposed to improve Quality of Service (QoS) through data classification [68–77]. Also, plenty of MAC schemes are presented to prioritize traffic using IEEE 802.15.4 such as [78–88] and using IEEE 802.15.6 such as [73,81,89–94].

Although, IEEE 802.15.4 supports two data communication modes, beacon, and non-beacon. However, in non-beacon mode, the superframe does not differentiate between active and inactive durations; thus, causing high energy consumption and collision [95]. The active duration has Contention Access Period (CAP) in beacon-enabled mode using Slotted Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). CSMA/CA is scalable with no constraints of time synchronization and it performs better in topological adjustments and low bandwidth. Also, it is a better choice for WBANs due to simpler implementation, lower delay and transmission reliability [41]. However, every BMSN contends during CAP for slot allocation; hence, increasing the probability of collision and affecting network performance regarding throughput, PDD, and energy. Therefore, many MAC schemes are proposed to prioritize contention-based traffic using slotted-CSMA/CA for IEEE 802.15.4 [25,27,28,96–99]. Similarly, in the beacon-enable mode of IEEE 802.15.6, heterogeneous-natured BMSNs contend in Exclusive Access Periods (EAP1 and EAP2), Random Access Periods (RAP1 and RAP2), and CAP for channel access using slotted-CSMA/CA. Thus, several MAC protocols are introduced to prioritize contention-based traffic using slotted-CSMA/CA for IEEE 802.15.6, such as [81,89,92–94].

1.1. Motivation

The contention-based traffic prioritization is of great significance because heterogeneous natured-BMSNs produce a variety of data packets with various degrees of importance. However, if all BMSNs simultaneously contend for channel access before packets transmission, then packet collision rate is increased. Therefore, network performance throttles down in terms of PDD, throughput, Packet Delivery Ratio (PDR) and energy consumption. Thus, contention-based prioritization is required to reduce the probability of collision and to improve the network performance regarding PDD, throughput, Packet Delivery Ratio (PDR) and energy consumption. So, many contention-based traffic priority MAC protocols are proposed. Their proposal is based on various techniques. Like, some of them provide contention-based traffic prioritization through the adjustment of both Backoff Exponent (BE) and Contention Window (CW) whereas some of them adjust either BE or CW. Further, some of the existing works utilize Backoff Counter (BC) to implement contention-based traffic prioritization. Besides, some of the existing works achieve contention-based traffic prioritization by using Backoff Period Ranges (BPRs). Alternatively, some of the current works adjust superframe sub-sections dynamically. However, every contention-based traffic prioritization technique has strengths and limitations that consequently affects the network performance.

1.2. Objectives of this study

This paper aims to present the limitations in the design of contention-based prioritization of heterogeneous traffic in WBANs MAC protocols to stimulate a better way of solving such limitations. We reviewed the literature chronologically but based on specific theme i.e., contention-based prioritization of heterogeneous traffic at MAC layer in WBANs. The papers are selected from the literature based on the following criteria. The selected papers are based on beacon-enabled IEEE 802.15.4 and IEEE 802.15.6 MACs. Further, only contention access phases of beacon-enabled MAC superframe are considered. Finally, in contention access phases, only slotted CSMA/CA algorithm is considered. On the other hand, the selected papers show their performance using following metrics: Packet Delivery Delay (PDD), Throughput (Th), Packet Delivery Ratio (PDR), and/or Energy Consumption (EC). Thus, in this paper, the performance of the selected papers is critically analyzed based on the aforementioned metrics.

1.3. Contributions

Analysis of slotted-CSMA/CA schemes (used in contention access phases of beacon-enabled IEEE 802.15.4 and IEEE 802.15.6 MACs) is provided regarding contention-based prioritization for heterogeneous traffic types. The challenges, classification, and comparative analysis of contention-based traffic priority MAC protocols are also presented. The contention-based traffic priority MAC protocols can be categorized into six: Adjustment of Backoff Exponent and Contention Window (ABECW), Adjustment of Backoff Exponent (ABE), Adjustment of Backoff Period Range (ABPR), Adjustment of Contention Window (ACW), Dynamic Adjustment of Superframe sub-Periods (DASP) and Adjustment of Backoff Counter (ABC). Further, the contention-based traffic priority MAC protocols are critically analyzed under the categorization mentioned above.

1.4. Paper organization

The rest of the paper is organized as follows. Table 1 represents the notations used in this article. Section 2 covers the related work. Section 3 discusses contention-based traffic priority MAC protocols in WBANs. Then in Section 4, a comparative analysis of contention-based traffic priority MAC protocols is presented wholly and categorically. In Section 5, the open issues and research challenges are discussed based on slotted-CSMA/CA of IEEE 802.15.4 and IEEE 802.15.6 standards. Finally, in Section 6, the conclusion is provided.

2. Related work

Many review articles are published in WBANs. For instance, in [14], Cao et al. deliberately analyze energy consumption, network coverage, and communication data rate. In addition to that, WBANs enabling technologies and settler research projects are comprehensively reviewed. In [15], Latré et al. provide the WBANs communication architecture. In addition, they briefly present current research trends in various communication layers such as physical, MAC, routing, and cross with future directions. In [37], Khan et al. discuss the healthcare applications approach and present methods for energy-efficient MAC design. The authors concluded that MAC is the appropriate layer to enhance network performance. In [36], Rahim et al. discuss design prerequisites to enhance the energy efficiency of WBAN and the strength and constraints of existing MAC protocols. In [100], Rashidi and Mihailidis focus ambient intelligence approach with assisted living tools for older adults. They also discuss current sensor and assistive robotics technology issues, human factors, and security.

Further, several research works cover WBANs MAC in general. Such as, [101], Movassaghi et al. explain IEEE 802.15.6 with recent studies in physical, MAC, and routing layers. They also focus on channel modeling and security. In [102], Cavallari et al. discuss WBAN's design issues, standards, methods, applications, technological aspects, and challenges to enhance the network performance. In [50], Bradai et al. also describe WBANs design needs with performance evaluation of TMAC, IEEE 802.15.4, and IEEE 802.15.6 in different working conditions; conclude that these protocols face a longer delay. In [103], Ayatollahitafti et al. describe WBANs standards for communication and required metrics for better network performance. They discuss physical, MAC, routing, and application layers requirements in the light of existing studies and technological aspects. In [104], Jaimes and Desousa discuss applications of WBANs and introduce its taxonomy for clear understanding. In [105], Ghamari et al. focus on WBANs performance metrics such as delay, security, packet delivery ratio, data rates, and energy consumption. A comparative analysis of energy-efficient and reliable MAC protocols is also provided. The challenging issues of residential healthcare systems are discussed for successful communication with the inadequacy of the existing residential healthcare. Finally, an effective home healthcare infrastructure is proposed to observe older adults for early diagnosis of different diseases. In [106], Preethichandra et al. discusses architectures, communication protocols, security issues, antennas types and design, and energy management issues of WBANs.

Besides, many studies analyze WBANs MAC schemes in terms of energy efficiency. Among them include [48] that assesses MAC schemes regarding energy efficiency through the wake-up radio of implanted BMSNs. In [107], Jo et al. also discuss major energy depletion attacks with future directions to improve energy efficiency at the MAC layer. Some studies also focus on Quality of Service (QoS) enabled MAC protocols in WBANs. For instance, in [47], Thapa et al. highlight the design requirements to achieve QoS at the MAC layer. They discuss current challenging issues to enhance the QoS at WBANs MAC layer and present a comparative analysis of existing QoS-aware MAC schemes.

Additionally, some researchers explore traffic adaptive MAC protocols, such as in [23], Masud et al. discuss IEEE 802.15.4 and IEEE 802.15.6 standards regarding traffic adaptivity in WBANs. They also

Table 1
Index of Key Notations.

Symbol	Description
BE	Backoff Exponent
NB	Number of Backoffs
CW	Contention Window
$macMaxCSMABackoffs$	Maximum number of backoffs at MAC layer
$macMinBE$	Minimum number of backoff exponent
$aMaxBE$	Maximum number of backoff exponent
$EAP\ 1$	Exclusive Access Period 1
$EAP\ 2$	Exclusive Access Period 2
$RAP\ 1$	Random Access Period 1
$RAP\ 2$	Random Access Period 2
UP	User Priority
$CW_{min}[UP]$	Minimum Contention Window size for specific User Priority
$CW_{max}[UP]$	Maximum Contention Window size for specific User Priority
CW_{double}	Doubling the size of Contention Window
BC	Backoff Counter
$pSIFS$	Short Inter-Frame Space
T_{diff}	Difference between current access phase duration and current time plus CSMA slot duration
T_{spec_frame}	Time required to complete specific frame transmission
T'_{diff}	Difference between the end of current access phase duration and the end of current CSMA slot duration
CW_{min}	Minimum Contention Window size
CW_{max}	Maximum Contention Window size
ACK	Acknowledgement
$CW0$	Contention Window 0
T_i	i^{th} Traffic Class value
$T_{class-value}$	Traffic Class value
D_{type}	Traffic Class value
$Class$	Traffic Class value
TC	Traffic Class value
Pkt_{CLT}	Packets Current Lifetime
$CURRENT\_TIME$	Virtual Simulation Time
$mac\rightarrow txtime(packet)$	Time taken by sender node during transmission of current packet plus link propagation delay
$wph\rightarrow MHR_{timestamp}$	Current virtual simulation time against all types of data packets when their MAC Protocol Data Unit (MPDU) is constructed
U_{max}	Maximum Contention Window size
$MIFS$	Medium Interframe Space
$SIFS$	Short Interframe Space
$LIFS$	Long Interframe Space
CW_{CP}	Contention Window for Critical Data Packets
CW_{DP}	Contention Window for Delay Sensitive Data Packets
CW_{RP}	Contention Window for Reliability Sensitive Data Packets
CW_{OP}	Contention Window for Ordinary Data Packets
$CW_{min,i}$	Minimum Contention Window size for i^{th} user priority
$CW_{max,i}$	Maximum Contention Window size for i^{th} user priority
$CW_{min,7}$	Minimum Contention Window size for 7th user priority
SW_i	Sliding Window for i^{th} user priority
β	Random Backoff number
WL_i	Maximum Window Limit of i^{th} traffic priority
TP_i	i^{th} traffic priority
f	Number of collisions
CI	Contention Index
α	Number of contending nodes
$MaxAllowableNodes$	Maximum Allowable Nodes
RBI	Random Backoff Index
RB	Random Backoff
BSI	Buffer Status Index
B_{occu}	Number of occupied cells in sensor node's buffer
RI	Retransmission Index
R	Number of retransmissions
R_{max}	Total number of retransmissions allowed
μ	Value of all parameters in PBCR
W_i	i^{th} parameter weight
$PGRI$	*Packet Generation Rate Index*
$\mathscr{A}$	Sum of CI, RBI, BSI, RI, and $PGRI$

provide a relative analysis of existing traffic adaptive MAC protocols for WBANs. On top of that, few researchers provide a critical review on emergency traffic MAC protocols for WBANs, such as, in [33], MASUD et al. present a thematic review of it. They critically perform emergency-based analysis of IEEE standards for WBANs. They critically compare existing emergency-based MAC protocols. A comparative analysis of existing emergency-based MAC protocols is provided regarding energy efficiency, delay, and packet delivery ratio. Some researchers focus solutions for signcryption security, like, in [10], Hussain et. al. comparatively analyze current signcryption solutions for WBANs using multi-criteria decision-making. Besides, Javadpour, Sangaiah [108] contributes by analyzing WBANs MAC regarding security. On the other hand, in [109], various WBANs-based medical applications are described with respect to various aspects, such as, communication frequency, energy

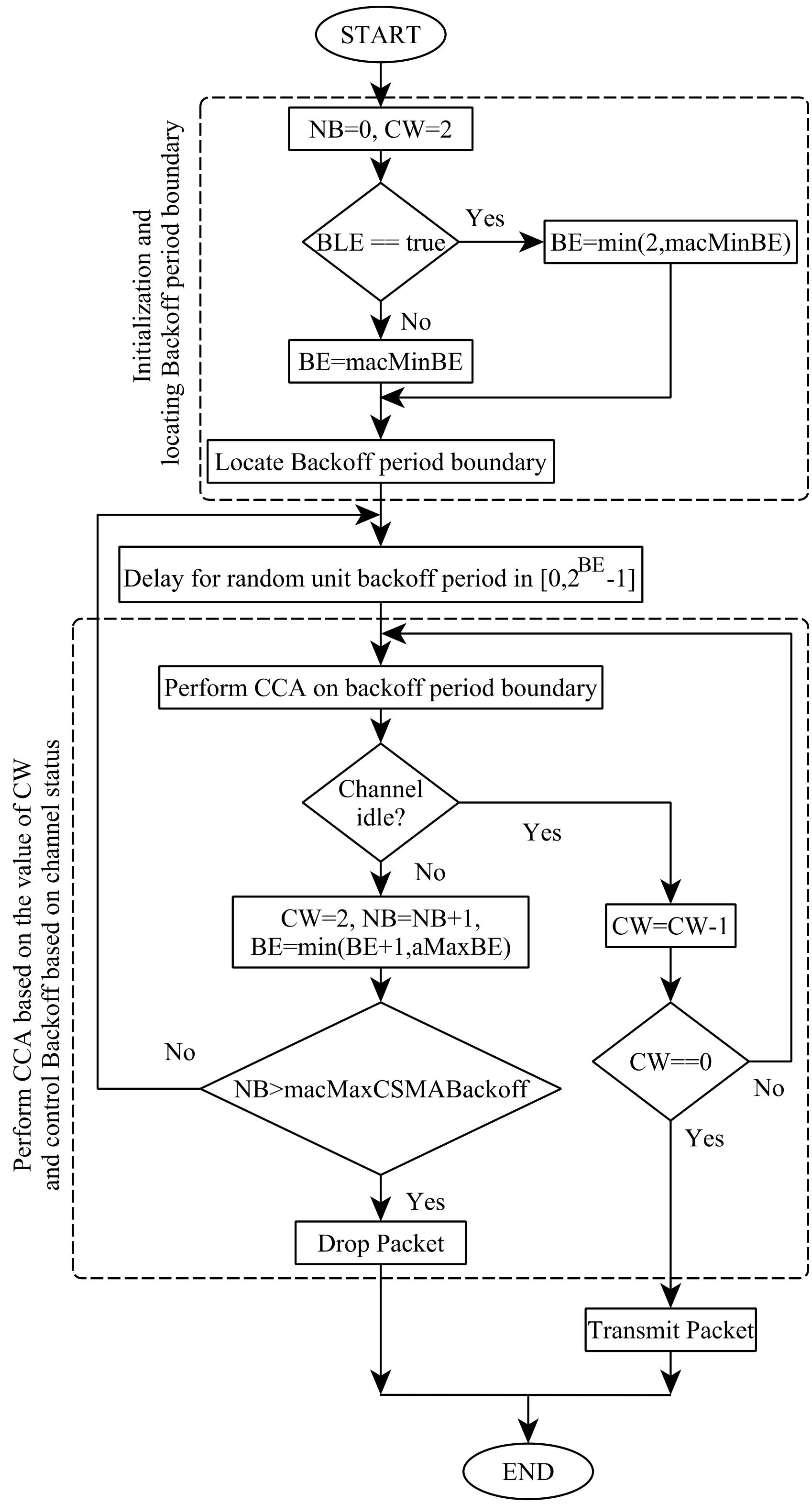

Fig. 2. Slotted-CSMA/CA scheme used in Contention Access Period of the beacon-enabled mode of IEEE 802.15.4 MAC [112].

efficiency, routing protocols, and end-user satisfaction. Some researchers target the integration of IoT and Blockchain in Healthcare, such as, in [110], Hegde and Maddikunta reviewed the integration of healthcare services and applications with IoT and Blockchain. In [111], Aski et al. critically reviewed IoT-enabled healthcare applications, protocol standard specifications, and their security frameworks.

In general, from the above-highlighted literature, most of the existing critical reviews focus on WBANs. Undoubtedly, no survey work focuses on contention-based traffic priority MAC protocols in WBANs, and this article focuses on filling this gap.

3. Contention-based traffic priority Mac protocols in WBANs

Heterogeneous natured BMSNs generate different types of data packets comprising vital-signs information and therefore require prioritized channel access. Pandit, Sarker [27] has categorized the vital-signs information into emergency data (i.e., sporadic by nature), critical data (both delay and reliability constrained), reliability data, delay data, and normal data. Yoon, Ahn [26], Anjum, Alam [25], Pandit, Sarker [27], and Rasheed, Javaid [28] have provided contention-based traffic priority MAC protocols. Traffic prioritization must be considered in WBANs due to the limited resources. Data collection from BMSNs has various degrees of significance; hence, the emergency and highly important data should be transmitted before the less important data [26]. Every heterogeneous-natured BMSN contends for slot allocation during contention; therefore, contention-based traffic prioritization is required to reduce the collision probability that affects overall network performance. However, contention-based traffic prioritization is much more significant for WBANs.

3.1. Analysis of slotted-CSMA/CA schemes based on traffic prioritization

The following subsections first describe and then analyze the slotted-CSMA/CA schemes used in contention access periods of IEEE 802.15.4 and IEEE 802.15.6 MAC's regarding traffic prioritization.

3.1.1. Slotted-CSMA/CA scheme used in contention access period of beacon-enabled IEEE 802.15.4 Mac

Every heterogeneous-natured BMSN contends in CAP for data transmission or slot allocation by using slotted-CSMA/CA in beacon-enabled mode. According to Fig. 2, three variables: Backoff Exponent (BE), Contention Window (CW), and Number of Backoffs (NB), are used by slotted-CSMA/CA. The BE calculates backoff periods, according to which each BMSN waits before channel access. CW is equivalent to eight backoff periods, and each BMSN waits for a clear channel before transmission. Slotted-CSMA/CA use NB during each transmission attempt [112].

In the start, slotted-CSMA/CA initializes NB by 0 and CW by 2. A constant value of 3 is given to macMinBE (i.e., the minimum number of backoffs), and a constant value of 5 is given to aMaxBE (i.e., the maximum number of backoffs). If Battery Life Extension (BLE) is true, then 2 is given to BE; else, a constant macMinBE is given to it. BC notifies the subsequent Beacon Interval (BI); thus, BMSNs locate the next backoff period boundary. Afterwards, every BMSN waits for random unit (i.e., selected from range $0-[2^{BE}-1]$) backoff periods.

Each BMSN performs Clear Channel Assessment (CCA) for collision avoidance. In the case of an idle channel, the value of CW is decremented by 1. Further, BMSN again performs CCA in the case of non-zero CW with channel status verification. The value of CW is again decremented by 1 in the case of an idle channel. However, the value of CW becomes zero; thus, BMSN transmits data through the obtained channel. In the case of the busy channel, CW resets to 2, NB and BE are incremented by 1, but BE must be less than or equal to aMaxBE. The packet is dropped by BMSN and slotted-CSMA/CA scheme is terminated if NB crosses macMaxCSMABackoffs. Alternatively, if NB <= macMaxCSMABackoffs, next backoff is started. In addition, a maximum of five backoffs are performed for channel access against each packet. Each BMSN picks a random number from the range [0 – 7] and completes the backoff period for the selected number of times in the first backoff. A random number is selected from [0 – 15] in the second backoff. Then, a random number is selected from [0 – 31] in the third backoff. Finally, fourth and fifth backoffs also use the range [0 – 31] for random number selection.

3.1.1.1. Analysis of Slotted-CSMA/CA scheme used in contention access period of Beacon-enabled IEEE 802.15.4 Mac regarding traffic prioritization. Firstly, in each backoff, the assigned Backoff Period Range (BPR) is the same for all types of BMSNs; thus, channel access is not prioritized for heterogeneous-natured BMSNs in slotted-CSMA/CA of IEEE 802.15.4 MAC. Consequently, it increases the collision rate, which results in high PDD, low PDR, and high energy consumption. Secondly, the upper limit of each BPR is calculated by using the value of BE variable, which remains 5 in the 4th and 5th backoffs. Actually, all BMSNs choose random unit backoff numbers from the same BPR [0 – 31] (i.e., calculated from $0-[2^{BE}-1]$) in 3rd, 4th, and 5th backoffs, as shown in Table 2. Thus, the aforementioned non-prioritized channel access again increases the collision ratio; consequently, the overall network performance is decremented.

Thirdly, as shown in Table 2, the BPR [0 – 7], i.e., used by all the BMSNs during their 1st backoff, is repetitively used as a subpart in the BPRs of 2nd, 3rd, 4th, and 5th backoffs. Similarly, the BPR [0 – 15], i.e., used by all the BMSNs during their 2nd backoff, is repetitively used in the BPRs of 3rd, 4th, and 5th backoffs. However, such repetitions in BPRs also increase the collision rate, which causes low PDD and high energy consumption. Last but not least, all BPRs start from zero; therefore, a low-priority BMSN can obtain the channel prior to a high-priority BMSN. Hence, the transmission of high-priority emergency data packets is delayed by early transfer of the low-priority data packets. Even though considering low priority normal traffic is essential in an emergency [113], emergency traffic requires the highest priority [76,114]. Hence, such delays are inappropriate for high-priority emergency traffic.

3.1.1.2. Slotted-CSMA/CA scheme used in contention-based periods of Beacon-enabled IEEE 802.15.6 Mac. Every heterogeneous-natured BMSN contends in EAP1, RAP1, EAP2, RAP2, or CAP for slot allocation by using slotted-CSMA/CA in beacon-enabled mode. Each BMSN receives a beacon frame that has information regarding each access phase's start and end times. The BMSNs with the highest priority data packets contend for slot allocation in EAP1 and EAP2. The access phases EAP1 and RAP1 can be merged as EAP1, and the access phases EAP2 and RAP2 can be merged as EAP2 to allocate contended slots for the highest priority data packets. On the other hand, the BMSNs with various user priorities contend for slot allocation in RAP1, RAP2, and CAP.

According to Fig. 3, if BMSN requires contended slot allocation for the first time or requires another contended slot allocation after the completion of its previous successful transmission, then the BMSN assigns $CW_{min}[UP]$ to its CW. Suppose BMSN requires retransmission in case of transmission failure. Then, its CW remains unchanged if the total count of consecutive retransmission failures is an odd number, but its CW value is multiplied by 2 or doubled in case of an even number. Further, if CW_{double} exceeds $CW_{max}[UP]$, then $CW_{max}[UP]$ is assigned to CW; otherwise, the CW_{double} is assigned to CW.

Also, the BMSN initializes its Backoff Counter (BC) by a random number selected from the range [1, CW] and then locks it. Afterward, the BMSN listens to the Short Inter-Frame Space (*pSIFS*) time channel. If the channel is busy, BMSN waits until the channel is free; otherwise, it computes T_{diff}, i.e., the difference between the current access phase duration and the current time plus CSMA slot duration. If enough time is available for one or more frames transmission, i.e., represented by $(T_{diff} >= T_{spec\_frame})$, BMSN unlocks its BC; otherwise, wait for the next access phase; where T_{spec_frame} represents the time required to complete

Table 2
BPRs Against Varying Values of BE Based-On Standard Slotted-CSMA/CA of IEEE 802.15.4 MAC.

NB = NB + 1 Initial value of NB = 0	BE = min(BE + 1, aMaxBE) Initial value of BE = 3	aMaxBE (constant)	macMaxCSMABackoff(constant)	NB > macMaxCSMABackoffs	BPR = $[0 - (2^{BE}-1)]$
0	3	5	4	FALSE	[0 – 7]
1	4	5	4	FALSE	[0 – 15]
2	5	5	4	FALSE	[0 – 31]
3	5	5	4	FALSE	[0 – 31]
4	5	5	4	FALSE	[0 – 31]
5	5	5	4	TRUE	—

min = mathematical function used to find the minimum value from two given values,
$[0 - (2^{BE}-1)]$ = Standard BPR Equation.

specific frame transmission.

Further, when the CSMA slot begins, the BMSN computes T_{diff}' (i.e., the difference between the end of current access phase duration and the end of current CSMA slot duration). If enough time is available for one or more frames transmission, i.e., represented by $(T_{diff}' >= T_{spec\_frame})$, BMSN performs CCA; otherwise, lock its BC and wait for the next access phase. If the channel is idle during CCA, BMSN decrements its BC by 1; otherwise, lock its BC, wait until the channel is free, and perform all steps again after the start of the CSMA slot. If the BC becomes zero, BMSN transmits the frame and waits for acknowledgment; else, BMSN waits until the start of the next CSMA slot and performs all steps again until BC becomes zero. If BMSN receives an expected acknowledgment frame, then it is to verify that either the transmitted frame's UP is greater than or equal to the last frame's UP or not. If true, BMSN waits for *pSIFS* time before transmitting the frame; otherwise, the contended allocation is finished. If BMSN fails to receive an expected acknowledgment, it deallocates and performs IEEE 802.15.6 slotted-CSMA/CA again for new allocation to re-transmit its frame.

3.1.1.2.1. Analysis of slotted-CSMA/CA scheme used in contention-based periods of Beacon-enabled IEEE 802.15.6 Mac regarding traffic prioritization. Firstly, the IEEE 802.15.6 [115] unveils prioritized channel access for eight traffic classes, out of which only three traffic classes are kept for medical applications. Nevertheless, the classification for medical applications is not formed according to heterogeneous-natured vital-signs data of the human body. Secondly, as shown in Table 3, the Backoff Counter Range (BCR) of the highest user priority is utilized as a subset in the BCRs of lower user priorities in each backoff; thus, delaying high priority traffic. Thirdly, short BCRs are given to the BMSNs having emergency and high-priority medical data in the first backoff, resulting in a high collision. Fourthly, the same BCR is given to each user priority class in every odd backoff; therefore, throttling down network performance regarding packet delivery delay, energy consumption, and throughput.

According to Table 3, the standard slotted-CSMA/CA prioritizes traffic through differentiated contention window bounds. But the backoff counter ranges of user priorities 0 and 1, 2 and 3, 4 and 5 are similar in the first four consecutive backoffs. In contrast, the backoff counter ranges of user priorities 1 and 2, 3 and 4, 5 and 6 are similar in fifth and onward backoffs. Hence, a separate contention window is not assigned to each user priority in every backoff. However, such repetitions of backoff counter ranges increase the collision and decrease the overall network performance.

3.2. Challenges of contention-based traffic priority Mac protocols in wbans

The design of contention-based traffic priority MAC protocols for WBANs applications is challenging due to its unique constraints. The main objective of contention-based traffic priority MAC protocols is to provide prioritized channel access based on the degree of traffic significance to reduce collision rate. So, WBANs should classify traffic based on the nature of BMSNs, and prioritize the developed classification based on the degree of importance. The following properties are required to design contention-based traffic priority MAC protocols.

3.2.1. Design of MAC superframe structure

The heterogeneous natured BMSNs observe various vital-signs and generate different types of delay sensitive data packets. Due to different types of delay sensitive data packets, sufficient number of higher bandwidth channels are required to save data packets from overlapping. Also, it is necessary that Beacon Interval (BI) and Superframe Duration (SD) have enough number of time periods for data transmission without waiting for the announcement of the next BI. Thus, it is necessary to modify MAC superframe structure to improve packet delivery ratio and energy efficiency.

3.2.2. Traffic classification

Contention-based traffic priority MAC protocols require the classification of traffic. Therefore, most of the existing traffic priority MAC protocols for WBANs classify the traffic into various categories such as critical, reliability, delay, and normal [25,26,89,116]. Moreover, several MAC protocols introduce another special-purpose traffic class, i.e., emergency traffic [68,70–77,117]. However, traffic classification is practically context-dependent [116].

3.2.3. Traffic prioritization

There are multiple ways to provide contention-based prioritization in WBANs. Some of the existing works provide contention-based traffic prioritization through the adjustment of Backoff Exponent (BE) and CW such as [95,118,119], while some of them only adjust BE like [25,27,28,96] and CW for example [89,92,120,121]. Besides, some of the existing works focus backoff counter for traffic prioritization [93,94]. Then, some achieve traffic prioritization by varying the BPRs like the case of [26,97–99]. A few existing works prioritize traffic by adjusting the superframe sub-sections dynamically for example [81,114,122].

3.3. Classification of contention-based traffic priority Mac protocols in wbans

The consideration of traffic prioritization during the contention period is of great significance because heterogeneous natured-BMSNs generate traffic with various degrees of importance. In addition, every BMSN contends for slot allocation during contention. Moreover, the contention-based traffic prioritization reduces the probability of collision, which affects the network's overall performance. So, the main goal of each contention-based traffic priority MAC protocol is to reduce collision rate, PDD, retransmission rate, and energy consumption and to increase PDR and throughput. The contention-based traffic priority MAC protocols in WBANs are designed using either IEEE 802.15.4 or IEEE 802.15.6 MAC, each of them is described in the following sections. Fig. 4 shows the existing state-of-the-art approaches in the classification tree.

3.3.1. Using slotted CSMA/CA scheme of Beacon-enabled IEEE 802.15.4 MAC

The contention-based traffic priority MAC protocols using slotted-

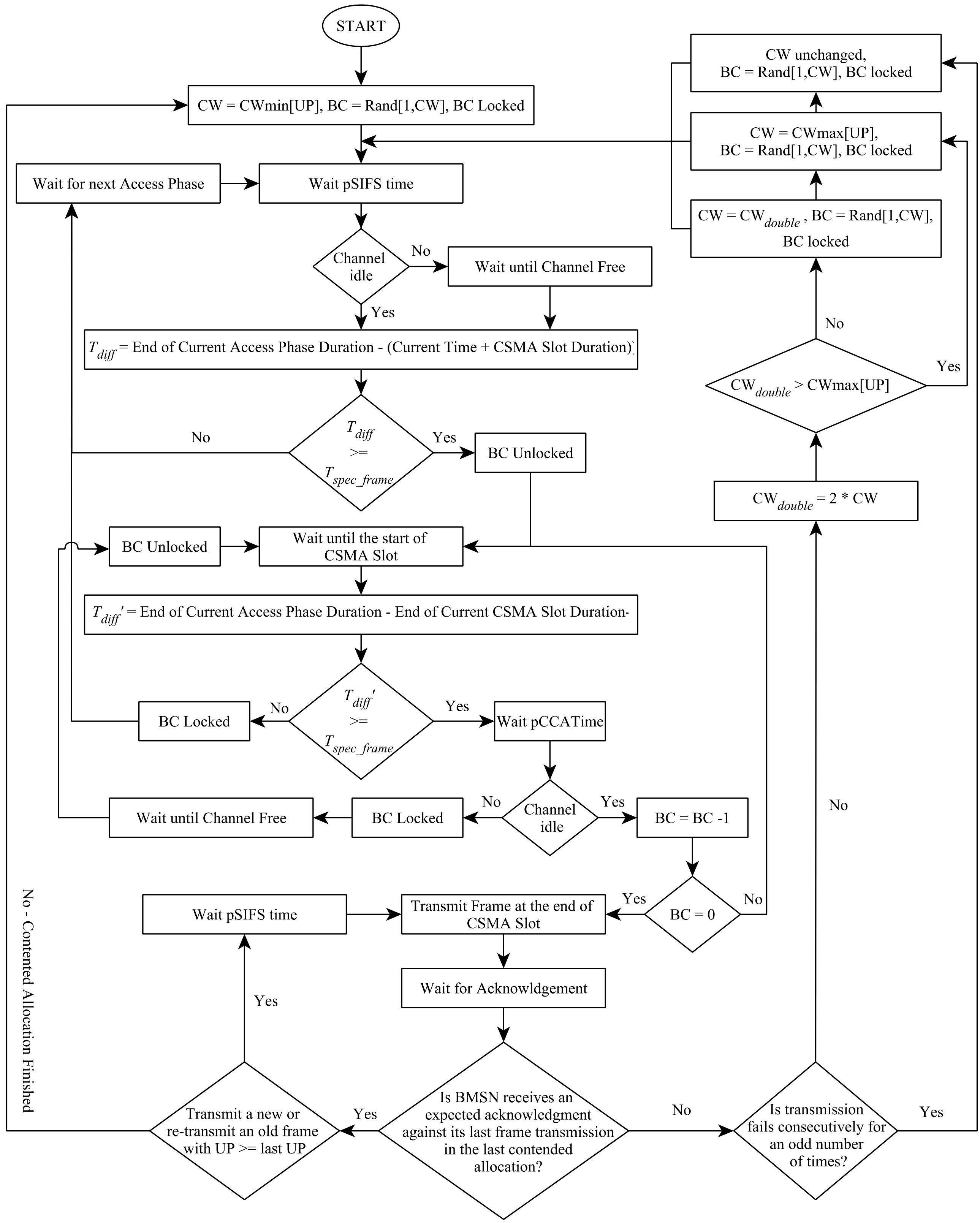

Fig. 3. Design of IEEE 802.15.6 CSMA/CA [94].

CSMA/CA of IEEE 802.15.4 standard can be classified into five; adjustment of backoff exponent and contention window, adjustment of backoff exponent, adjustment of backoff period range, adjustment of contention window, and dynamic adjustment of superframe sub-periods. Each of them is mentioned in the following sub-sections. Likewise, various existing approaches that use them are summarized and reviewed in detail.

3.3.1.1. Adjustment of backoff exponent and contention Window (ABECW). The paper by [118] proposes a Multi-level Service

Table 3
Contention Window Bounds for Standard Slotted-CSMA/CA of IEEE 802.15.6 MAC.

User Priority (UP)	CWmin	CWmax	CW = CWmin	Initial Backoff Counter Selection Range[1, CW]	Backoff Counter Selection Ranges (1st even number try for Transmission)[1, CW]	Transmission fails consecutively for even number (1st) of times = 2 * CW	CW = min (CW, CWmax [UP])	Backoff Counter Selection Ranges (2nd odd number tryfor Transmission) [1, CW]	Backoff Counter Selection Ranges (2nd even number try for Transmission) [1, CW]	Transmission fails consecutively for even number (2nd) of times = 2 * CW	CW = min (CW, CWmax [UP])	Backoff Counter Selection Ranges (3rd odd number tryfor Transmission) [1, CW]
0	16	64	16	[1–16]	[1–16]	32	32	[1–32]	[1–32]	64	64	[1–64]
1	16	32	16	[1–16]	[1–16]	32	32	[1–32]	[1–32]	64	32	[1–32]
2	8	32	8	[1–8]	[1–8]	16	16	[1–16]	[1–16]	32	32	[1–32]
3	8	16	8	[1–8]	[1–8]	16	16	[1–16]	[1–16]	32	16	[1–16]
4	4	16	4	[1–4]	[1–4]	8	8	[1–8]	[1–8]	16	16	[1–16]
5	4	8	4	[1–4]	[1–4]	8	8	[1–8]	[1–8]	16	8	[1–8]
6	2	8	2	[1–2]	[1–2]	4	4	[1–4]	[1–4]	8	8	[1–8]
7	1	4	1	[1–1]	[1–1]	2	2	[1–2]	[1–2]	4	4	[1–4]

CW = Contention Window, UP = User Priority.
min = mathematical function used to find the minimum value from two given values.
Note:
- Backoff Counter Selection Ranges used in 3rd odd number try for transmission remains unchange afterwards.
  User Priority: 7th is highest and 0 is lowest.

Differentiation (MSD) Scheme for IEEE 802.15.4 to improve throughput and packet delivery delay. The slotted-CSMA/CA algorithm in beacon-enabled IEEE 802.15.4 MAC is considered during saturation conditions (i.e., SNs always have packets waiting for transmission). All Sensor Nodes (SNs) are distributed among various priority classes where high priority SNs gain better QoS than low priority SNs. Service differentiation is proposed for multiple priorities classes by two mechanisms. The first is differentiated contention window size, and the second is differentiated backoff exponent. In the differentiated contention window size mechanism, a prioritized CW value is assigned to different SNs based on their priority classes. A lower CW value is assigned to high priority class SN, and a higher CW value is assigned to lower priority class SN. Likewise, a prioritized BE value is assigned to various SNs based on their priority classes in a differentiated backoff exponent mechanism.

Furthermore, a Discrete-time Markov chain mathematical model is also presented for the proposed differentiated mechanisms. This mathematical model obtains channel access probability of SNs, saturation throughput, and delay. It is claimed that prioritized CW is more effective for service differentiation than prioritized BE, whereas prioritized BE is comparatively better to achieve low average packet delivery delay. However, if zero is given to CW of highest priority class SN, after the first CCA, the value of CW becomes negative in case of an idle channel which is impractical. On the other hand, if value one is given to CW of highest priority class SN, after first CCA value of CW becomes zero and packet is transmitted which is collided with ACK message of the previous packet, thus, dropped. Since one-time CCA takes 8 symbols time whereas ACK message is received after approximately 16 symbols, at least two CCA's are required. In addition, the CW of lowest priority class SN initializes with value three, which delays the low priority packets due to unnecessary three-time CCA.

The paper by [119] introduces a Priority-based Service Differentiation (PSD) Scheme for IEEE 802.15.4 to improve throughput, packet delivery ratio, and packet delivery delay. The slotted-CSMA/CA is considered for a non-saturation environment. The authors propose two multilevel service differentiation mechanisms: backoff exponent differentiation (BED) and contention window differentiation (CWD). In BED, a differentiated backoff exponent is assigned to various priority classes. A smaller BE is given to a high priority class, and a larger BE is provided to a low priority class. Thus, SN with smaller BE accesses the channel before SN with larger BE.

Similarly, in CWD, a prioritized contention window is assigned to different priority classes. A smaller CW is given to the high priority class, and a larger CW is provided to the low priority class. Hence, a high-priority SN starts transmission while a low-priority SN performs CCA. A discrete-time Markov chain mathematical model analyzes the performance of the proposed mechanisms. Moreover, a criterion is designed to find out the optimal length of the superframe based on numerical results. Besides, the number of units backoff periods are obtained to process SN's head packets. BED mechanism improves channel utilization and service differentiation irrespective of SNs and packet arrival rate. By applying a prioritized backoff exponent and a prioritized contention window, PSD shows better network performance regarding throughput, packet delivery ratio, and packet delivery delay. However, the highest priority SN directly performs CCA because its BE is initialized by zero value. After the first CCA, if the channel is idle, the value of its CW0 becomes −1. Besides, channel status is again verified because CW is not equal to CW0. If the channel is idle, CW0 is again decremented by value 1, which is again not equal to CW; therefore, the proposed algorithm is stuck in an infinite loop until the channel is idle. Thus, 2nd highest priority packets obtain the channel before the highest priority packets. In addition, after the adjustment of CW0, SN directly checks the channel status without performing CCA, which is an unrealistic approach. In addition, the adaptive parameter setting with low PDD requires more energy, which is hard to achieve due to the random nature of the slotted CSMA/CA. Besides, the adaptive parameter setting creates ambiguity for various networks and traffic patterns [123].

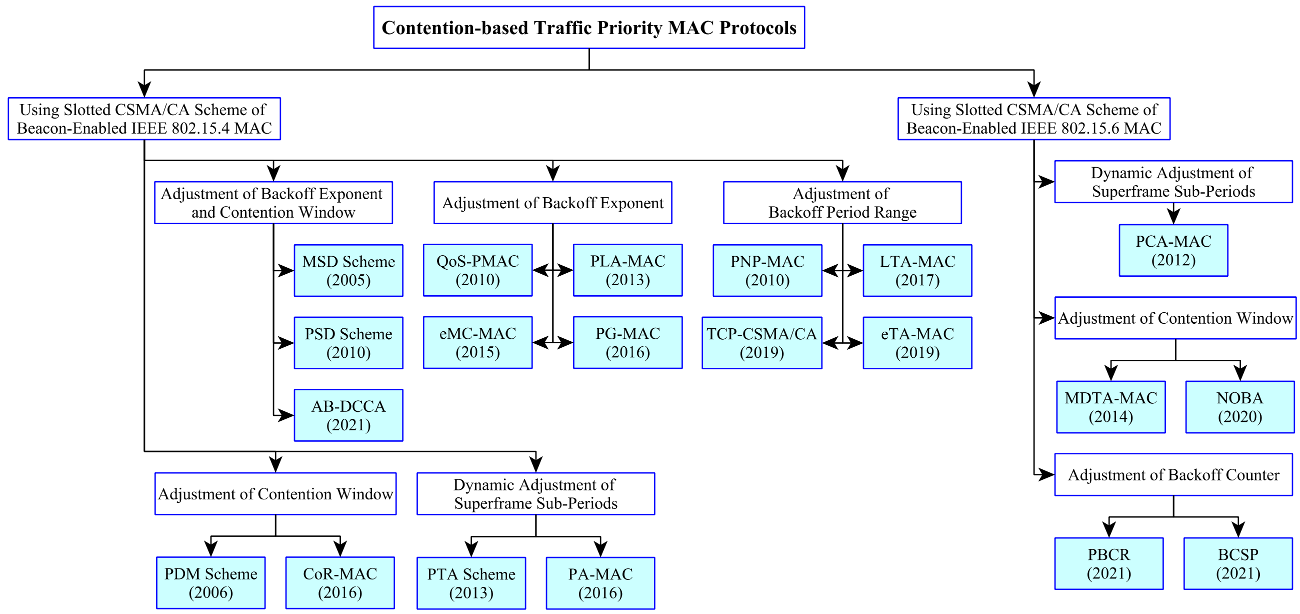

Fig. 4. Classification of Contention-based Traffic Priority MAC protocols in WBANs.

The Adaptive Backoff and Dynamic Clear Channel Assessment (AB-DCCA) mechanisms are proposed by [124] to improve throughput, PDR, end-to-end delay, and residue energy in a highly dynamic environment. The distinct BPRs are proposed for the first three backoffs to reduce collision probability. In addition, the standard CCA algorithm is customized for optimized channel access to improve the network performance regarding energy, channel utilization, and packet delivery delay. The proposed mechanisms are analyzed through the Markov chain model to assess whether the proposed mechanisms enhance the network performance or not. The proposed distinct BPRs for different backoffs reduce collision to some extent. The proposed CCA mechanism assigns zero to CW when the channel is idle, and CW has value 1. Resultantly, it improves throughput and PDR and reduces end-to-end delay. However, the same BPR is given to all traffic types in every backoff; thus, traffic is not prioritized. In addition, performing one-time CCA causes a collision between the transmitted packet and acknowledgment of the previous packet. Therefore, it affects network performance in terms of throughput, PDR, and end-to-end delay.

3.3.1.2. Adjustment of backoff exponent (ABE). The Quality-of-Service Provisioning MAC (QoS-PMAC) scheme is suggested by [96] to provide traffic prioritization for on-time transmission of emergent traffic with continuous transmission of periodic data. Also, the authors aim to reduce queueing delay, improving throughput and saving more energy. The authors classify the traffic as: Alarm Control (AC), Command Data (CD), and Routine Traffic (RT), where AC has the highest, the CD has second highest, and RT has the lowest priority. The traffics AC and CD are transmitted through contended channel access in the CAP. A distinct BE value is chosen for AC and CD, so 0 is assigned to BE for AC traffic,2 is assigned to BE for CD traffic, and a bigger number is assigned to BE for RT traffic. Every successful transmission in CAP is terminated after the reception of the acknowledgment frame. However, AC packets compete with CD packets in their 3rd, 4th' and 5th backoffs, which causes a collision; thus, it increases PDD and energy consumption and reduces the throughput. In addition, 0 is selected as a random backoff number for AC traffic, and the random backoff number for CD traffic is selected from the range started from 0. Therefore, the BMSN with CD traffic can choose 0 or the value close to 0 as a random unit backoff number, results in the collision between AC and CD traffic. Hence, the QoS-PMAC scheme fails to provide traffic prioritization comprehensively.

The traffic Priority and Load-Aware MAC (PLA-MAC) protocol [25] presents contention-based traffic prioritization to improve network performance regarding throughput, PDD, and energy. The authors classify the traffic into four critical classes, reliability, delay, and ordinary data packets based upon data type and data generation rate. Critical data packet class has 0 as traffic class value, reliability class has 1, delay class has 2, and ordinary class has 3 as traffic class value. The low-class value represents higher priority, and the higher-class value illustrates low priority compared to the other classes. Every BMSN performs contended channel access based on a backoff value selected from the BPR, where T_i represents traffic class value. A distinct T_i is given to each traffic class by replacing BE with T_i. Thus, each traffic class gets a distinct BPR in its first backoff, but the assigned BPR remains same until the last backoff. Consequently, increasing PDD and energy consumption rate and decreasing the throughput. In addition, the BPRs assigned to low priority traffic classes are the superset of BPRs assigned to high priority traffic classes, which increases the collision among them. Thus, overall network performance is throttled down. Also, a very long BPR is given to the lowest priority traffic class, increasing the packet delivery delay [98].

An energy-efficient Multi-constrained QoS aware MAC (eMC-MAC) protocol is proposed by [27] to prioritize traffic with high energy efficiency. The authors categorize traffic into five classes, each having a distinct priority. All BMSNs perform prioritized random backoff by selecting backoff number from BPR, where $T_{class-value}$ is the traffic class value. The $T_{class-value}$ for critical and reliability packets is 0, urgent packets is 1, delay packets is 2, and non-constrained packets is 3. Therefore, critical and reliable packets use 0 as backoff value, urgent packets use [0 – 3] as BPR, delay packets use [0 – 15], and non-constrained packets use [0 – 63] as BPR. Although a distinct BPR is given to every traffic class except critical and reliability packets, the assigned ranges remain unchanged until the last backoff. Thus, increasing the packet drop rate, which influences the scheme's performance regarding PDD and energy. Also, critical and reliable packets perform contended channel access without delay by directly performing CCA. Hence, the collision is increased between critical and reliable packets, which again increase the packet delivery delay. Further, BPRs of high priority Traffic Classes (TCs) are utilized as a subset in the BPRs of low priority TCs which also raises collision and retransmission rate; thus, increasing PDD and decreasing on-time success ratio and energy efficiency. Alike PLA-MAC, a very long BPR is given to the lowest priority traffic class in eMC-MAC; thus, it increases the packet delivery delay [98].

A Priority Guaranteed MAC (PG-MAC) protocol is presented by [28] to provide contention-based prioritization of heterogeneous traffic with low PDD and less energy consumption. The authors classify the traffic into three categories that are Emergency Data (ED), Periodic Data (PD), and Normal Data (ND). ED has the lowest D_{type}(i.e., traffic class value) value, PD has higher D_{type} value, and ND has the highest D_{type} value. All BMSNs perform prioritized random backoff by selecting a random backoff value from the proposed BPR, $[0To2^{D_{type}}+2]$, where D_{type} is used instead of BE (used in the standard BPR equation). Even though a distinct BPR is given to every TC in its first backoff by assigning various D_{type} values to different traffic classes, each assigned range remains the same until the last backoff. Thus, packet collision rate increases, which resultantly raises retransmission and energy consumption rates. In particular, the BPR of high priority traffic class is utilized as a subset in the BPRs of low priority traffic classes; thus, causing congestion and increased collision rate, which throttles down the overall network performance.

3.3.1.3. Adjustment of backoff period range (ABPR). The paper by [26] presents Preemptive and Non-Preemptive MAC (PNP-MAC) protocol to prioritize traffic for diverse traffic types with reduced heterogenous PDD and improved throughput. The authors consider five traffic types from which the highest priority is given to emergency alarm and the second-highest priority to continuous medical traffic. Further, the sequence of priority is as follows: medical routine, non-medical continuous, and then the lowest priority is given to other types of traffic, which include file transfer. The authors distribute the above traffic types into three backoff classes that are 0, 1, and 2. All BMSNs contend during CAP through prioritized random backoff and CCA to access the channel. Every BMSN selects the random backoff number for contended channel access from the range, $[0To2^{BE}(Class+1)-1]$, where Class is a variable that represents traffic class value. In the first backoff where BE is by default 3, the BPR $[0-7]$ assigns to a 0th traffic class, $[0-15]$ is given to traffic class 1, and $[0-23]$ is given to traffic class 2. The assignment of different BPRs for various traffic types reduces heterogenous PDD and raises the throughput. However, the assigned BPR to high priority traffic class is a subset of the BPRs that are assigned to low priority traffic classes, which can cause non-prioritized channel access. Also, the assigned BPRs remain unchanged in 3rd, 4th, and 5th backoffs; thus, increasing packet collision and retransmission rate, and as a result, PDD is increased. Further, the BPRs assigned to traffic classes 1 and 2 have a high upper limit, i.e., 63 and 95, respectively. Hence, traffic classes 1 and 2 face a longer packet delivery delay in their 3rd, 4th and 5th backoffs.

In Low-delay Traffic-Aware Medium Access Control (LTA-MAC) protocol [97], Ullah et al. introduce a Contention Differentiated Adoptive Slot Allocation CSMA/CA (CDASA-CSMA/CA) scheme to provide contention-based prioritized channel access through the assignment of distinct BPR in each backoff. The authors also target improving network performance regarding PDR, delay, and energy. The authors classify the traffic into ordinary and critical data packets. The BPR $[0\text{ To }2^{\mathrm{BE}}-1]$ is given to all traffic classes as in slotted-CSMA/CA of IEEE 802.15.4 MAC. Then, a BPR $[2^{\mathrm{BE}-1}\text{ To }2^{\mathrm{BE}}-1]$ is proposed to assign all the traffic classes in their 2nd, 3rd, 4th, and 5th backoffs. A different BPR is given in every backoff, which improves network performance regarding PDR, PDD, and energy consumption. However, the assignment of the same BPR to all BMSNs in each backoff results in high collision and retransmission. Also, several BMSNs find a busy channel in their 1st backoff, which forces them to go for 2nd, 3rd, or maybe 4th backoff; hence, delaying the transmission of patient's vital-signs data. In addition, a short BPR is assigned in each backoff which causes congestion; consequently, it throttles down the network performance regarding PDR, delay, and energy.

Traffic Class Prioritization-Based Slotted-CSMA/CA (TCP-CSMA/CA) scheme is introduced by [98] to introduce contention-based traffic prioritization with improved network performance regarding throughput, PDD, PDR, Packet Loss Ratio (PLR), and energy consumption. Traffic is classified into four classes. The highest priority is given to Critical Traffic Class (CTC), followed by Reliability Traffic Class (RTC), Delay Traffic Class (DTC); and lowest priority is assigned to Non-constraint Traffic Class (NTC). The standard slotted-CSMA/CA is uniquely enhanced by proposing a distinct BPR for each backoff as follows:

For 1st backoff:

$$\mathrm{TC}\,2^{(BE+1)}\ To\ 2^{BE}+4\mathrm{TC}+1 \tag{1}$$

For 2nd backoff:

$$2^{BE}\,(\mathrm{TC}+1)\ To2^{BE}+4\mathrm{TC}+3 \tag{2}$$

For 3rd backoff:

$$2^{BE}(\mathrm{TC}+1)-4\mathrm{TC}\ To2^{BE}+4\mathrm{TC}+3 \tag{3}$$

For 4th backoff:

$$2^{(BE-1)}+4(\mathrm{TC}+1)To2^{BE}+4\mathrm{TC}-1 \tag{4}$$

For 5th backoff:

$$2^{(BE-1)}+4\mathrm{TC}\ To2^{(BE-1)}+4\mathrm{TC}+3 \tag{5}$$

where BE represents backoff exponent, TC represents traffic class. Also, every traffic class obtains a distinct BPR, computed from the proposed BPR in each backoff. The network performance is upgraded notably by proposing a distinct BPR for every TC in each backoff. However, the computation of a distinct BPR for each TC in every backoff poses a computational overhead on BMSNs [125]. Consequently, it increases the energy consumption and packet delivery delay and decreases the throughput.

The emergency Traffic Adaptive MAC (eTA-MAC) is presented by [99] to achieve traffic prioritization during contended channel access in the absence or presence of emergency traffic with emergency-based balance among throughput, delay, and energy. Three schemes are proposed: TCP-CSMA/CA, ETCP-CSMA/CA, and ETA-CSMA/CA. These schemes cooperate to achieve better network performance regarding throughput, delay, and energy consumption. In the start, BMSN initializes its parameter and locates the backoff period boundary, then performs TCP-CSMA/CA in case of a normal situation or ETCP-CSMA/CA in case of emergency. Afterward, the 1st backoff of TCP-CSMA/CA is performed in both cases. Later on, BMSN performs CCA and then verifies whether the channel is idle. If the channel is busy, then increments NB and BE, and CW is reset to 2 similar to standard slotted-CSMA/CA. Afterward, it is to verify that either value of NB crosses the maximum limit or not. If the packet is dropped else, go for the next backoff under TCP-CSMA/CA scheme. If the channel is idle, then transmit the packet in case of a normal situation or perform ETA-CSMA/CA in emergency.

In particular, ETCP-CSMA/CA aims to transmit contention-based sporadic emergency traffic instantaneously with minimal delay but without disregarding non-emergency data packets in the CAP. In ETCP-CSMA/CA, four BMSNs observe heartrate, respiratory rate, temperature, and blood pressure, considered as Expected Emergency-BMSNs (EE-BMSNs). The Emergency Traffic Class (ETC) is proposed for EE-BMSNs which is generated dynamically and gains highest priority by stepping down all TCs in case of emergency. Further, ETC is removed when emergency resolves and all TCs resume its priority level. On the other hand, ETA-CSMA/CA scheme targets dynamic adjustment of traffic to accommodate dynamic changes in diverse traffic rates with energy saving of non-emergency traffic BMSNs and create equilibrium between energy consumption and throughput in sporadic emergency situation. ETA-CSMA/CA introduces a system to manage the lifetime of all packet types in emergency. Thus, it maintains the lifetime of all packet types and drops the expired packets before transmission. The following equation is proposed by eTA-MAC to calculate the current lifetime of particular data packet.

$$Pkt_{CLT} = \text{CURRENT\_TIME} + mac{\rightarrow}txtime(packet) - wph{\rightarrow}MHR_{timestamp} \quad (6)$$

where Pkt_{CLT} represents packets current lifetime, CURRENT_TIME is the virtual simulation time, $mac{\rightarrow}txtime(packet)$ is the time taken by sender node during transmission of current packet plus link propagation delay. $wph{\rightarrow}MHR_{timestamp}$ stores current virtual simulation time against all types of data packets when their MAC Protocol Data Unit (MPDU) is constructed. eTA-MAC improves network performance regarding PDD, throughput, and energy consumption and creates equilibrium between energy consumption and throughput. Nevertheless, in ETA-CSMA/CA, the lifetimes of emergency and non-emergency data packets are computed without analyzing channel conditions. Thus, most data packets may expire before reaching the destination in the worst channel conditions, even though they succeeded in the lifetime criterion of ETA-CSMA/CA. eTA-MAC improves network performance regarding PDD, throughput, and energy consumption and creates equilibrium between energy consumption and throughput. Nevertheless, in ETA-CSMA/CA, the lifetimes of emergency and non-emergency data packets are computed without analyzing channel conditions. Thus, most data packets may expire before reaching the destination in the worst channel conditions, even though they succeed in the lifetime criterion of ETA-CSMA/CA.

3.3.1.4. Adjustment of contention Window (ACW). The paper by [120] proposes a Priority-based Delay Mitigate (PDM) Scheme for IEEE 802.15.4 LR-WPANs to reduce the delay and provide timely delivery of high-priority data packets. Authors classify packets into two categories: normal and high priority. PDM scheme introduces frame tailoring and priority to methods for prioritization. The frame tailoring removes collision between the acknowledgment of previous data packet and newly transmitted data packet by adjusting the length of data packets; thus, acknowledgment is received after exactly 12 symbols. The number of CCA is reduced from two to one time before transmitting the next data packet by adjusting the contention window size. In priority toning, the Coordinator Node (CN) listens to the channel in a backoff slot before starting the beacon interval. CN broadcasts the beacon frame at the start of the beacon interval. If connected sensor node(s) send a tone to CN, the beacon frame is updated and notified accordingly. Therefore, the sensor nodes with low priority packets postpone their transmissions for a specific period, whereas those with high priority packets contend for channel access during this specific period. Hence, packet type-based adaptation of a single CCA prioritizes urgent data packets [123]. However, the transmission rescheduling of top priority data packets due to their frame length adjustment results in high delay [123].

The Contention over Reservation MAC (CoR-MAC) is proposed by [121] to improve channel utilization and reduce delay. CoR-MAC considers three types of data: urgent, time-critical, and non-time-critical. The urgent packets have the highest priority, while non-time-critical packets have the lowest priority, and the priority of time-critical packets is in the middle. Typically, CoR-MAC introduces a dual reservation mechanism. In the proposed mechanism, initially, time slots are reserved for sensor nodes expecting urgent traffic. Afterward, if any reserved slot is currently not utilized while other sensor nodes require data transmission, access the reserved slot through contention. Since the nature of urgent data is sporadic, the temporary reservation of non-urgent data packets in the CAP can be given to urgent data sporadically. For this purpose, a non-urgent packet waits for Medium Inter-Frame Space (MIFS) before transmission, but an urgent packet waits for Short Inter-Frame Space (SIFS) where SIFS < MIFS.

Furthermore, urgent packets use a customized contention window, selected from (0, U_{max}) where $U_{max} <$ MIFS −SIFS. On the other hand, prioritizing time-critical and non-time-critical packets is applied by delaying non-time-critical packets to wait for Long Inter-Frame Space (LIFS), where SIFS < LIFS. Hence, a reserved time slot can be utilized by various traffic types, which improves channel utilization and reduces delay. However, non-urgent packets may be ignored by increasing the number of sensor nodes having urgent packets [23].

3.3.1.5. Dynamic adjustment of superframe sub-Periods (DASP). A Priority-based adaptive Timeslot Allocation (PTA) scheme is proposed by [122] to improve QoS for various traffic types. PTA categories the traffic into 3 classes C_1 (i.e., emergency alarm), C_2 which is further divided into C_{21} (i.e, continuous medical) and C_{22} (i.e., discontinuous medical), and C_3 (i.e, continuous non-medical). The CAP is divided into three sub-phases, and the length of each phase is calculated and adjusted dynamically regarding the number of SNs (joining or leaving) the network. The C_1 traffic can be transmitted through all three phases; C_2 traffic uses the last two phases for data transmission while C_3 performs transmission through the last phase. Further, phase-I exists even though C_1 traffic is absent, capturing only the first timeslot. C_1 and C_{22} transmit data through contended channel access while C_{21} and C_3 contend during CAP to allocate Guaranteed Time Slot (GTS). All SNs utilize standard slotted CSMA/CA algorithm during contended channel access. PTA scheme provides priority-based adaptive phase allocation in the CAP. However, the phase level prioritization mechanism is not provided for SNs belonging to different priority classes, contending during phases II and III.

In [114], the Priority-based Adaptive MAC (PA-MAC) protocol is introduced to decrease contention complexity among heterogeneous nature WBANs traffic during channel access in the CAP with low energy consumption. This scheme categorizes the traffic into four classes: emergency traffic with P_1 (highest) priority, on-demand traffic with P_2 priority, normal traffic with P_3 priority, and non-medical traffic with P_4 (i.e., lowest priority). The CAP period is divided into four sub-phases (as shown in Fig. 5) based on the delay requirements of WBANs. If a particular traffic type crosses its default delay value, the CAP is divided into "the number of traffic types that crosses default delay value + 1" sub-phases. Moreover, the 1st sub-phase for P_1 traffic, 2nd sub-phase for P_1 and P_2 traffic, 3rd for P_1, P_2, and P_3, and 4th sup-phase for all traffic types. However, PA-MAC attempts to reduce contention complexity, but traffic prioritization is not provided for single phase CAP. In addition, multiple traffic types compete parallelly to obtain the channel in 2nd, 3rd, and 4th sub-phases, again raising the contention complexity. Thus, causing the collision among packets of different traffic classes; therefore, overall traffic is delayed.

3.3.2. Using slotted CSMA/CA scheme of Beacon-Enabled IEEE 802.15.6 MAC

The contention-based traffic priority MAC protocols using slotted-CSMA/CA based on IEEE 802.15.6 standard can be classified into three: dynamic adjustment of superframe sub-periods, adjustment of contention window, and adjustment of backoff counter. We describe each of them in the following sub-sections. Similarly, various existing approaches that use them are summarized and reviewed in detail.

3.3.2.1. Dynamic adjustment of superframe sub-Periods (DASP). In [81], Priority-based Channel Access MAC (PCA-MAC) protocol is proposed to reduce the contention complexity among the heterogeneous-natured information of WBANs applications during channel access in the CAP period. The authors categorize the traffic into four classes: medical, general health, mixed medical and non-medical, and non-medical services. The medical service is the highest traffic class, general health has the second-highest priority, mixed medical and non-medical has the third-highest priority, and non-medical service is the lowest priority traffic class. A delay threshold is used to divide the CAP period into four sub-phases based upon the delay requirements of WBAN (i.e., 125 ms for medical traffic and 250 ms for non-medical traffic). For example, if the highest priority traffic class is delayed more than 125 ms, the CAP period

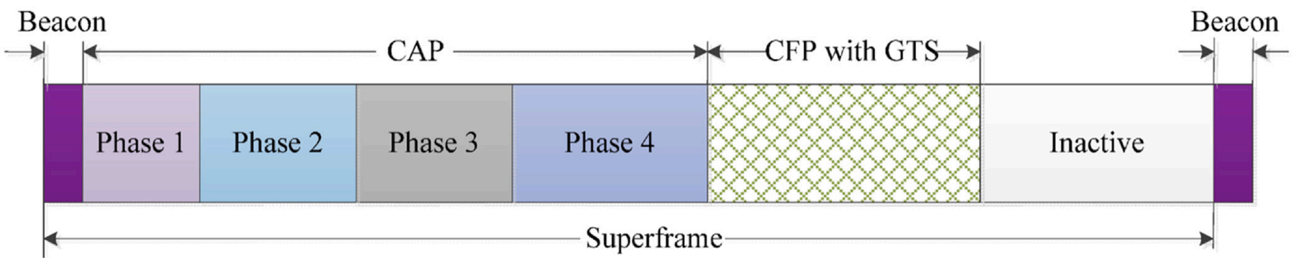

Fig. 5. PA-MAC Superframe with CAP divided into four Phases[114].

is divided into two sub-phases. The 1st sub-phase is for the highest priority traffic class, i.e., medical service, and the 2nd phase is for all traffic types, including the medical service. Further, if the second priority traffic class is also delayed, CAP is divided into three sub-phases. First sub-phase for level 0 traffic, i.e., medical service, second sub-phase for level 0 and 1 traffic class, and third for all traffic classes including level 0 and 1. PCA-MAC reduces contention complexity through prioritization-based graded channel access. However, PCA-MAC attempt to minimize the contention complexity but does not provide any phase-level prioritization mechanism in the CAP. Thus, all traffic types contend simultaneously for channel access. It results in a collision among packets of various traffic classes, thus, delaying the overall traffic and causing multiple sub-phases in the CAP. In addition, multiple traffic types compete parallelly to obtain the channel in 2nd, 3rd, and 4th CAP sub-phases, again raising the contention complexity.

3.3.2.2. Adjustment of Contention Window (ACW). A Multi-Dimensional Traffic Adaptive MAC (MDTA-MAC) protocol [89] is presented to minimize energy costs and delays. The authors use four traffic classes with prioritization. They consider CP as emergency traffic. The traffic is classified into four categories: Critical Packet (CP), Delay Sensitive Packet (DP), Reliability Sensitive Packet (RP), and Ordinary Packet (OP). The highest priority is CP (also considered emergency traffic class), followed by DP RP; the lowest priority is OP. They propose two operation modes in the superframe on the basis of traffic loads to adjust the traffic dynamically. In the case of low-load and moderate-load traffic, all BMSNs use prioritized backoff and Contention Window (CW) to access the channel for data transmission in the Exclusive Access Phase (EAP) and CAP periods. In case of an emergency, when traffic load becomes high or overload, BMSNs with CP and DP packets use prioritized backoff and CW to access the channel for data transmission in EAP. The BMSNs with RP and OP packets use prioritized backoff and CW to access the channel for slot allocation in RAP. The RP and OP traffic is transmitted through allocated slots in RAP to save the energy of BMSNs with non-emergency traffic. The CW is zero in the absence of a specific traffic class. The CW ranges of various traffic types are calculated from the following proposed equations:

For CP

$$CW_{CP} = 0 \approx (\frac{CW_{max}}{N} - 1) \tag{7}$$

For DP

$$CW_{DP} = \frac{CW_{max}}{N} \approx (\frac{2CW_{max}}{N} - 1) \tag{8}$$

For RP

$$CW_{RP} = \frac{2CW_{max}}{N} \approx (\frac{3CW_{max}}{N} - 1) \tag{9}$$

For OP

$$CW_{OP} = \frac{3CW_{max}}{N} \approx CW_{max} - 1 \tag{10}$$

where CW_{max} is the maximum contention window size and has the value 32, whereas N is not defined in MDTA-MAC, but a value of 4 is assigned to it. Thus, traffic class CP gets the range 0 – 7 (i.e., calculated from equation (7), DP gets 8 – 15 as selected CW range, RP gets the CW range 16 – 23, and OP gets 24 – 31 as CW range. MDTA-MAC proposes distinct CW ranges for various traffic classes. When traffic load increases due to an emergency, then transmission of emergency traffic or CPs requires more slots in the EAP phase to manage the high traffic load, resulting in an increasing length of the EAP phase. This increasing length of the EAP phase reduces the transmission opportunity of non-emergency RP and OP traffic. Therefore, the BMSNs with RP or OP traffic consumes more energy due to a long delay in transmission. Further, many CPs found busy channels in their first backoff and are bound to opt for the second backoff for channel access. Still, unfortunately, MDTA-MAC does not propose any mechanism of CW selection for second, third, or fourth backoffs. It means CPs always use proposed equation no. 7 to calculate CW range (i.e., 0 – 7), thus CPs in second, third, or fourth backoff delay newly coming CPs in its first backoff.

A Non-Overlapping Backoff Algorithm (NOBA) is introduced by [92] to avoid backoff-based inter-priority collisions. The NOBA considers all Traffic Priorities (TPs) defined by IEEE 802.15.6. The sensor nodes of every TP choose random number from the range $[CW_{min,i}, CW_{max,i}]$ where $i = 0 - 7$. At the start of each beacon interval, $CW_{min,7}$ and SW_i are initialized by 1 for TP 7. The value of $CW_{max,i}$ is computed by adding $CW_{min,i}$ and SW_i for every TP. Further, CW_{min} of every lower TP is computed by adding 1 and CW_{max} of the next higher TP. The SW_i is incremented by 2 in an even number of collisions, but it remains unchanged for an odd number of collisions. Fig. 6 presents the packet transmission design of NOBA in which β represents the random backoff number while WL_i shows the maximum window limit of each TP, and f is a counter to manage the number of collisions. NOBA provides a discrete range to each TP sensor node to select random backoff numbers during contended channel access in every backoff. However, the short CW ranges raise the collision if higher TP sensor nodes packet generation rate increases due to emergency. Further, the assignment of short CW ranges in every backoff also throttles down the overall network performance when the number of sensor nodes is increased in various TPs.

3.3.2.3. Adjustment of backoff Counter (ABC). In [93], a Parameter-based Backoff Counter Regulation (PBCR) method is incorporated in IEEE 802.15.6 CSMA/CA to select BC value. PBCR considers all traffic priorities which are considered by IEEE 802.15.6. In the existing IEEE 802.15.6 CSMA/CA, the BC value is selected randomly, whereas, in the proposed method, its selection depends upon different contextual parameters. Further, it is claimed that the proposed method improves the network performance regarding throughput, transmission reliability, and collision ratio. The following contextual parameters are used by PBCR: contention, random backoff, buffer status, packet generation, and retransmission indices. All indices are calculated from the following proposed equations:

Contention Index (CI)

$$CI = \frac{\alpha}{MaxAllowableNodes} \tag{11}$$

Random Backoff Index (RBI)

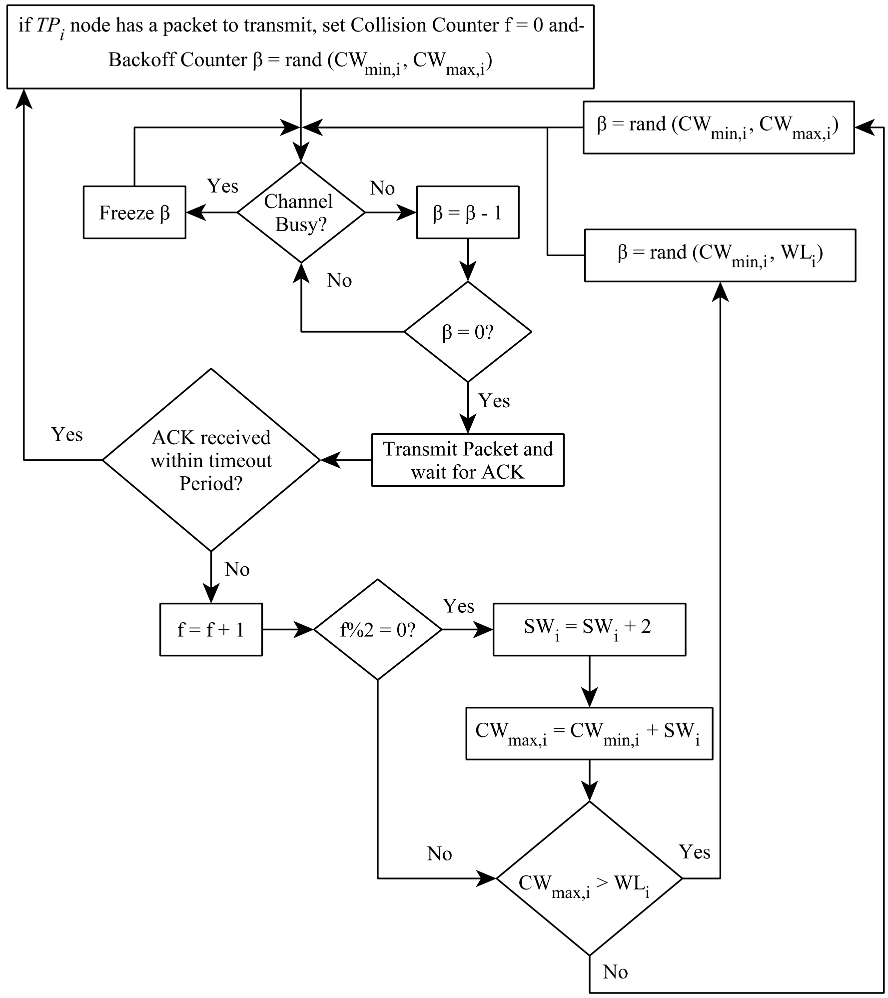

Fig. 6. Packet Transmission Design of NOBA [92].

$$RBI = \frac{RB}{CW_{max}[UP]} \tag{12}$$

Buffer Status Index (BSI)

$$BSI = 1 - \frac{B_{occu}}{BufferSize} \tag{13}$$

Retransmission Index (RI)

$$RI = 1 - \frac{R}{R_{max}} \tag{14}$$

μ

$$\mu = \frac{\sum_{i=1}^{N} W_i \times \mathscr{A}_i}{\sum_{i=1}^{N} W_i} \tag{15}$$

BC

$$BC = Ceil(\mu \times CW_{max}[UP]) \tag{16}$$

In the equations, α represents the number of contending nodes, RB is random backoff selected from [1, CW], $CW_{max}[UP]$ is the maximum CW of specific user priority, B_{occu} represents number of occupied cells in sensor node's buffer, R is the number of retransmissions, R_{max} is the total number of retransmissions allowed, $\mathscr{A}$ represents sum of CI, RBI, BSI, RI, and PGRI, and parameters at a particular time W_i is i^{th} parameter weight, N is the number of parameters and μ is value of all parameters. Ceil function is used to round the resultant value. Equation number 16 is calculated for a specific user priority sensor node by using its maximum CW value and values of its contextual parameters (calculated by using equations (11) – (15).

Finally, an additional step is inserted in IEEE 802.15.6 CSMA/CA after performing step 1(i.e., CW = $CW_{min}[UP]$, BC = Rand[1, CW], BC Locked) but before step 2 (i.e., Wait *pSIFS* time) of Fig. 2 and BC is replaced by RB in step 1. Considering contextual parameters based on user priority uniquely enhanced IEEE 802.15.6 CSMA/CA, but computation of PBCR by each user priority sensor node in every backoff poses high computational overhead on sensor nodes. Consequently, it increases energy consumption and packet delivery delay and decreases the throughput. Further, the calculated value of BC (by using proposed equation (16) is very high, which crosses even $CW_{max}[UP]$ in the first go. Hence, traffic from the sensor nodes of various user priorities is delayed; thus, it increases collision rate and throttles down transmission reliability.

A Backoff Counter Selection Procedure (BCSP) is introduced by [94] to improve backoff counter selection criteria for medical data and enhance network performance regarding collision rate, waiting time during idle listening, and transmission reliability. Three medical data types are considered: emergency, high priority, and normal. User priority 1 is proposed for an emergency, 2 for high priority, and 3 for normal medical data. Based on CW intervals, a distinct BC selection criterion is proposed for each medical data type. In an emergency, BC is randomly selected from the range [1,3]. In case of high priority and normal data, the selection of BC is made by performing four functions, Exist, Select, Lock and Unlock. The main objective to perform the functions above is to select the minimum CW value, which is not currently used by any other sensor node. Further, a BC table is maintained to store those CW values already utilized by any sensor node. The Exist function verifies whether the specific CW value is already taken by any sensor node or not, which is done by checking table BC. The "Select" function chooses the minimum CW value, which is not currently utilized by any sensor node. Sensor node inserts the selected CW value in the table BC through the Lock function and removes that CW value from the table BC after utilizing the Unlock function. BCSP distinctively introduces a new mechanism to select a discrete value of BC for various traffic types. However, the minimum CW value is selected for high priority and normal data types from an undefined range. Besides, suppose high priority or normal data type selects CW value less than CW value (i.e., 3) of emergency data type. In that case, high priority or normal data can obtain the channel prior to emergency data. Thus, any traffic type can access the channel before any other traffic type, removing the concept of prioritization.

4. Comparative analysis of contention-based traffic priority MAC protocols

All aforementioned contention-based traffic priority MAC protocols intend to provide contention-based prioritized channel access mechanisms for WBANs. To design an efficient contention-based traffic priority MAC protocol that can provide data transmission with a low delay and energy consumption and high throughput and packet delivery ratio is a challenging job. Table 4 provides a comparison of aforementioned existing Contention-based Traffic Priority MAC protocols for WBANs, in terms of Traffic Classification (TC), Traffic Prioritization (TP), Number of TC's, Packet Delivery Delay (PDD), Throughput (Th), Packet Delivery Ratio (PDR), and Energy Consumption (EC) with their goal, strength, and limitation. Also, categorization-based critical comparative analysis is provided in the sub-sections.

4.1. Under ABECW category – IEEE 802.15.4

MSD scheme [118] intends to provide better QoS through prioritization. Therefore, MSD scheme achieves better QoS for high priority traffic through prioritized CW and reduces average packet delivery delay by the prioritization of BE. It assigns distinct but very short BPRs to various TC in the first backoff. Again, in the second backoff, distinct but very short BPRs are given to different TCs. The given ranges increase gradually but become very long for middle and low priority TCs in fourth and fifth backoffs. Thus, the collision ratio is raised, which prominently reduces throughput. In addition, if zero is assigned to CW of high priority SN, the value of CW becomes negative after the first CCA in case of the idle channel, and the MSD scheme gets stuck into an infinite loop. As a result, packet collision ratio raised, and the network performance of the MSD scheme is throttled down regarding PDD and throughput.

PSD scheme [119] aims to improve network performance via prioritization. It shows better network performance even in high traffic loads; achieved through the prioritization of BE and CW. PSD Scheme also proposes the same equations to calculate BPRs of various backoffs for different traffic classes. Therefore, facing similar problems as faced by the MSD scheme, but the criterion for CW value is different. In PSD scheme, initially CW = 0 for H (high) priority class SNs, CW = -1 for M (middle) priority class SNs and CW = -2 for L (low) priority class SNs. However, the H priority class SNs directly performs CCA because its BE is initialized by zero value. Thus, the high priority SNs face longer delay due to the assignment of zero value to its BE. After the first CCA, if the channel is idle, the value of its CW0 becomes −1. The channel status is again verified because CW is not equal to CW0. If the channel is idle, CW0 is again decremented by value 1, which is again not equal to CW; therefore, the PSD scheme gets stuck into an infinite loop until the channel is idle. Thus, M priority packets access the channel before H priority packets.

AB-DCCA [124] targets to achieve high throughput and low delay in a dynamic environment. It assigns a distinct BPR in every backoff to all traffic types which reduces delay and raises throughput and PDR to some extent. However, all traffic types contend to access the channel at the same level in the first backoff due to the assignment of same BPR to each traffic class in the first backoff. Resultantly, increasing PDD and energy consumption, and decreasing throughput and PDR. Further, it proposes one-time CCA when the channel is idle and CW == 1. Therefore, the packet transmitted after one-time CCA collides with the acknowledgment packet, i.e., coming from the destination against the previously transmitted packet. Thus, increasing packet collision ratio which affects network performance regarding throughput, PDR, PDD, energy consumption.

4.2. Under ABE category – IEEE 802.15.4

QoS-PMAC [96] targets timely transmission of emergency and periodic traffic with minimum delay and maximum possible throughput and energy efficiency. QoS-PMAC prioritized the BE to minimize queueing delay. Besides, a value 0 is selected as a random backoff number for AC traffic, whereas BPR 0 – 3 is given to CD traffic to select a random backoff number. So, the value 0 or close to 0 can be selected as a random backoff number for the BMSNs with CD traffic. Therefore, emergency traffic AC compete with non-emergency traffic CD for channel access. Thus, it raises collision between AC and CD traffic which resultantly delays emergency traffic and requires more energy for retransmission. Further, the assigned BPRs to BMSNs with AC or CD traffics remain the same in 2nd, 3rd, 4th, and 5th backoffs, which also causes a collision; thus, it increases PDD and energy consumption and reduces the throughput.

PLA-MAC [25] wants to achieve higher throughput and lesser PDD and energy consumption via the prioritization of contention-based traffic. For this purpose, it assigns distinct BPR to every TC in the first backoff, but the assigned BPRs remain same in next backoffs. As a result, collision ratio is increased which also raises PDD and energy consumption. The calculated BPRs for high priority TCs are the subset of calculated BPRs for low priority TCs; thus, SNs with low priority packets can choose random backoff numbers either equal to or less than random backoff numbers selected SN with high priority packets. Thus, high, and low priority SNs contend parallelly, again causing high collision among high and low priority packets which throttles down network performance regarding average PDD, throughput, and energy consumption. Again, a long calculated BPR 0 – 63 is given to OP (i.e., ordinary data packet belongs to lowest priority TC); thus, OP traffic faces a very long delay [98].

eMC-MAC [27] intends to achieve energy efficiency with traffic prioritization. eMC-MAC reduces collision which improves energy efficiency through the assignment of distinct BPR to various traffic classes except critical and reliability constrained traffic. However, the value 0 is given to CP (Critical Packet) and RP (Reliability constrained Packet); thus, increasing the collision between CP and RPs due to the high packet generation rate, which raises PDD. The BPRs assigned to CP, RP, UP (Urgent Packet), DP (Delay constrained Packets), and NP (No delay or reliability constrained Packet) are overlapped with each other, also causing congestion. Moreover, the given BPRs to various TCs remain the same in all five backoffs and, critical and reliability constrained packets directly perform CCA. Resultantly, raises collision and retransmission, increasing PDD and energy consumption and decreasing on-time success ratio. Last but not least, 0 – 63 BPR is assigned to NP which is very long comparatively; thus, delaying NP traffic [98]. PG-MAC [28] focusses lesser delay with minimized energy consumption through contention-based traffic prioritization. Again, like eMC-MAC, a distinct BPR is given to every TC only in the first backoff which slightly reduces delay and raises throughput but the assigned BPRs remain unchanged in the next backoffs which resultantly increases PDD and energy consumption. Further, the BPRs of ED, PD, and ND are overlapped with each other;

Table 4
Contention-based Traffic Priority MAC protocols.

IEEE Standard	Categorization	Protocol	Characteristics									
			Goal	TC	TP	Number of TCs	PDD	Th.	PDR	EC	Strength	Limitation
Based on Slotted CSMA/CA Scheme used in Contention Access Period of Beacon-Enabled IEEE 802.15.4 MAC	**ABECW**	MSD Scheme (2005)	To provide better QoS for various traffic classes through prioritization using differentiated CW size and BE during contended channel access.	Yes	Yes	3	Low	Medium	NC	NC	High priority traffic gets better QoS as compared to low priority traffic and this is done through prioritized CW whereas low average packet delivery delay is achieved by prioritized BE.	Inappropriate initialization of CW size for various traffic classes delays traffic from low priority class SNs and raises collision between the newly transmitted data packet from the high priority class SNs and ACK message against the already delivered data packet.
		PSD Scheme (2010)	To improve throughput, PDR and PDD by applying prioritized CW and BE.	Yes	Yes	3	Low	High	High	NC	Channel is utilized effectively with improved QoS due to proposed BED mechanism even in case of large number of SNs and high packet generation rate. PSD presents better network performance regarding throughput, PDR and PDD because of the proposed prioritized BE and CW.	Highest priority SN stuck in an infinite loop in case of idle channel due to the assignment of zero to BE, but the lower priority packets can access the channel. Further, adaptive parameter setting with low PDD require more energy which is hard to achieve due to random nature of slotted CSMA/CA. Besides, the adaptive parameter setting also creates ambiguity for various networks and traffic patterns [123].
		AB-DCCA (2021)	To improve network performance regarding throughput, PDR, PDD, and reduce energy in a highly dynamic environment.	Yes	Yes	3	Low	Medium	Medium	High	The assignment of distinct BPR for each backoff reduces collision and assignment of zero value to CW in case of idle channel also improves network performance regarding throughput and PDR, and PDD to some extent.	Traffic is not prioritized because same BPR is given to all traffic types in every backoff. In addition, reducing CCA to one-time causes collision between the newly transmitted packet and ACK of already delivered packet; thus, affecting network performance regarding throughput, PDR, and PDD.
	ABE	QoS-PMAC (2010)	To achieve on-time delivery of emergent traffic without ignoring continuous transmission of periodic traffic with reduced queuing delay, energy consumption and improved throughput.	Yes	Yes	3	Low	High	NC	Low	A distinct BE value is provided to all traffic types which slightly decreases queuing delay.	AC and CD packets compete with each other for contended channel access in their 3rd, 4th, and 5th backoffs which causes collision. In addition, random backoff number for AC packets is zero and for CD packets, selected from the range starting from zero; so, it gets zero or a value near to zero which again causes collision and delays emergent traffic AC. Hence, reducing network performance regarding PDD, EC, and throughput, and provides incomplete traffic prioritization.
		PLA-MAC (2013)	To provide contention-based traffic prioritization with higher	Yes	Yes	4	Medium	Medium	NC	High	A distinct BPR is assigned to each traffic class in its first	The assigned BPRs of first backoff remain unchanged until the last backoff and BPRs of low

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Table 4 (*continued*)

IEEE Standard	Categorization	Protocol	Characteristics									
			Goal	TC	TP	Number of TCs	PDD	Th.	PDR	EC	Strength	Limitation
			throughput, and less PDD and energy consumption.								backoff which reduces collision to some extent.	priority traffic classes are the super set of BPRs assigned to high priority traffic classes which result in a high collision among high and low priority packets. Thus, throttles down network performance regarding average PDD, throughput, and energy consumption. Further, a very long BPR is assigned to lowest priority traffic class, thus, facing a longer PDD [98].
		eMC-MAC (2015)	To provide traffic prioritization with low energy consumption	Yes	Yes	5	Medium	NC	Medium	Medium	A distinct BPR is given to every traffic class except critical and reliability packets; thus, reducing collision and energy consumption insignificantly.	The assigned ranges of first backoff remains unchanged until the last backoff; thus, increases packet loss ratio, PDD and energy consumption. Further, critical and reliability packets directly perform CCA which causes collision between critical and reliability traffic, increases PDD. The BPRs of high priority traffic classes are the subset of BPRs for low priority traffic classes, resulting high collision and retransmission rate which also raises PDD, and energy consumption. Last but not the least, very long BPR is given to lowest priority traffic class, as a result, traffic with lowest priority faces a very long PDD [98].
		PG-MAC (2016)	To lessen PDD and energy consumption through contention-based traffic prioritization.	Yes	Yes	3	Medium	Medium	NC	Medium	A distinct BPR is given to every traffic class in its 1st backoff by assigning various D_{type} values to different traffic classes which decreases PDD and energy consumption to some ratio.	A distinct BPR which is given to different traffic classes in the first backoff, remains unchanged until the last backoff. Further, BPR of high priority traffic class is used as a subset in the BPRs of low priority traffic classes. Thus, number of collisions are increased which results in higher PDD and energy consumption.
	ABPR	PNP-MAC (2010)	To decrease heterogenous PDD and to increase throughput through traffic prioritization for heterogenous traffic types.	Yes	Yes	5	Low	Medium	NC	NC	The assignment of different BPRs for heterogenous traffic types improve network performance to some extent regarding heterogenous PDD and throughput.	The BPR of highest priority class is used as a subset in BPRs of low priority classes. Also, the assigned BPRs remain unchanged after second backoff. Thus, number of collisions are increased which raises retransmission rate and as a result PDD is increased. Further, the BPRs assigned to traffic class 1 and 2 have high upper limits, i.

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Table 4 (*continued*)

IEEE Standard	Categorization	Protocol	Characteristics									
			Goal	TC	TP	Number of TCs	PDD	Th.	PDR	EC	Strength	Limitation
												e., 63 and 95 respectively. Hence, traffic from classes 1 and 2 faces a longer PDD if goes beyond second backoff during contention.
		LTA-MAC (2017)	To achieve better network performance regarding PDR, PDD, and energy consumption through traffic prioritization during contended channel access.	Yes	Yes	2	Medium	NC	Medium	High	A different BPR is given in every backoff which little bit improves network performance regarding PDR, PDD and energy consumption.	Every traffic class gets a same BPR at backoff level during contended channel access. Further, a short BPR is given in first and second backoff; thus, several BMSNs find busy channel in their first backoff which force them to go for second, third, or may be for fourth backoff. Hence, collision is increased which throttles down network performance regarding PDR, PDD, and energy consumption.
		TCP-CSMA/CA (2019)	To improve network performance regarding throughput, PDD, PDR, PLR, and energy consumption by contention-based traffic prioritization.	Yes	Yes	4	Low	High	High	Low	The network performance is improved prominently by proposing a distinct BPR for every traffic class in each backoff.	The computation of a distinct BPR for each traffic class in every backoff poses computational overhead on BMSNs [125] which insignificantly increases energy consumption and PDD, and decreases throughput.
		eTA-MAC (2019)	To upgrade network performance regarding throughput, PDD and energy consumption and creating a balance between throughput and energy consumption with the help of contention-based traffic prioritization in absence or presence of emergency traffic and by controlling the lifetime of data packets.	Yes	Yes	5	Low	High	NC	Low	The network performance in upgraded notably regarding throughput, PDD and energy consumption, and also successfully creating balance between energy consumption and throughput by assigning of a distinct BPR to each traffic class in every backoff and by monitoring lifetime of data packets.	Channel conditions are not considered during the computation of emergency and non-emergency data packets lifetime; thus, in case of worst channel conditions, majority of data packets may be expired before reaching destination.
	ACW	PDM Scheme 2006	To reduce PDD and improve on-time delivery of high priority data packets by introducing frame tailoring and priority toing methods.	Yes	Yes	2	Low	NC	Medium	NC	Top priority is given to urgent data packets by adapting single CCA [123]; thus, urgent data packets reach their destination on-time.	Transmission rescheduling of top priority data packets due to their frame length adjustment results in high delay [123].
		CoR-MAC (2016)	To improve channel utilization and reduce PDD by dual channel reservation and traffic prioritization.	Yes	Yes	3	Low	High	NC	Low	The allocation of reserved time slot used by various traffic types which improves channel utilization and reduces PDD	Non-urgent packets may be ignored by increasing the number of sensor nodes having urgent packets [23].
	DASP	PTA Scheme (2013)	To improve QoS for various traffic types.	Yes	Yes	3	NC	Low	Low	Medium	A priority-based adaptive phase allocation is proposed during CAP.	No phase-level prioritization mechanism is proposed for SNs belonging to various priority classes, contending during phase II and III.
		PA-MAC (2016)	To lessen the contention complexity among heterogeneous nature WBANs	Yes	Yes	4	Medium	Medium	NC	Low	Minimize contention complexity through adaptive phase allocation in the CAP	Traffic prioritization is not provided for single phase CAP; therefore, all traffic types

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Table 4 (*continued*)

IEEE Standard	Categorization	Protocol	Characteristics									
			Goal	TC	TP	Number of TCs	PDD	Th.	PDR	EC	Strength	Limitation
			traffic during contended channel access with reduced energy consumption.									compete parallelly to obtain the channel. In addition, multiple traffic types compete parallelly to obtain channel in 2nd, 3rd, and 4th sub-phases, raising contention complexity. Thus, causing collision among packets of various traffic types, delaying overall traffic.
Based on Slotted CSMA/CA Scheme used in Contention Access Period of Beacon-Enabled IEEE 802.15.6 MAC	**DASP**	PCA-MAC (2012)	To decrease the contention complexity among heterogeneous natured information of WBANs applications during contended channel access in the CAP with reduced energy consumption.	Yes	Yes	4	High	NC	NC	High	Reduces contention complexity through prioritization-based graded channel access	No phase-level prioritization mechanism is introduced for contended channel access; thus, packets of various traffic classes contend simultaneously for channel access at phase-level. As a result, collision is increased among the packets of various traffic classes; thus, delaying the overall traffic and causing multiple sub-phases in the CAP. In addition, multiple traffic types compete parallelly to obtain the channel in 2nd, 3rd, and 4th CAP sub-phases, again raising the contention complexity.
	ACW	MDTA-MAC (2014)	To minimize energy cost and delay.	Yes	Yes	4	High	NC	Medium	Low	The proposal of distinct CW ranges for various traffic classes reduces delay and energy cost to some extent.	If traffic load increases due to emergency, then the transmission of emergency packets or CPs requires more slots in EAP phase to manage high traffic load; thus, the length of EAP phase is increased. The grown length of EAP phase reduces the transmission opportunity for non-emergency RP and OP traffic, therefore, the BMSNs with RP or OP traffic consumes more energy due to a long delay in transmission. Further, many CPs found busy channel in their first backoff and are bound to opt second backoff for channel access but unfortunately MDTA-MAC do not propose any mechanism of CW selection for second, third or fourth backoffs. However, CPs always use the proposed CW range (i.e., 0 – 7) in second, third, or fourth backoff and contend simultaneously with CPs (which are in its first backoff) for channel access.

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Table 4 (*continued*)

IEEE Standard	Categorization	Protocol	Characteristics									
			Goal	TC	TP	Number of TCs	PDD	Th.	PDR	EC	Strength	Limitation
		NOBA (2020)	To avoid backoff-based inter-priority collisions.	Yes	Yes	8	Low	High	NC	Medium	A discrete CW range is given to each TP sensor node for the selection of random backoff number during contended channel access in every backoff which results in lower delay and energy consumption.	The given discrete CW ranges are short which raises collision if higher TP sensor nodes generate large number of packets due to emergency. Further, the assignment of short CW ranges in every backoff also throttles down the overall network performance when number of sensor nodes are increased in various TPs.
	ABC	PBCR (2021)	A parameter-based backoff counter method is incorporated in IEEE 802.15.6 CSMA/CA to select optimal value of BC and to improve network performance regarding delay and transmission reliability.	Yes	Yes	8	High	Medium	Medium	NC	The consideration of Contextual parameters based on user priority uniquely enhanced IEEE 802.15.6 CSMA/CA.	A high computational overhead is imposed on sensor nodes due to the computation of PBCR by each user priority sensor node in every backoff. Thus, increasing energy consumption and packet delivery delay and decreasing the throughput. Further, the proposed equation to calculate BC generates very high value of BC which crosses even $CW_{max}[UP]$in the first go. Resultantly, delaying traffic from all sensor nodes that belong to various user priorities and also throttling down transmission reliability.
		BCSP (2021)	To improve backoff counter selection criteria for medical data and to upgrade network performance regarding collision rate, waiting time during idle listening and transmission reliability.	Yes	Yes	3	High	Low	Low	NC	A new mechanism is distinctively introduced to select discrete value of BC for different traffic types.	The minimum CW value is selected for high priority and normal data types from undefined range. Besides if high priority or normal data type selects CW value which is less than CW value (i.e., 3) of emergency data type then high priority or normal data can obtain the channel prior to emergency data. However, the concept of traffic prioritization is not implemented properly.

TC = Traffic Classification**, TP** = Traffic Prioritization**, PDD** = Packet Delivery Delay**, Th.** = Throughput, **PDR** = Packet Delivery Ratio**, EC** = Energy Consumption, **NC** = Not Considered.
ABECW = Adjustment of Backoff Exponent and Contention Window, **ABE** = Adjustment of Backoff Exponent, **ABPR** = Adjustment of Backoff Period Range.
ACW = Adjustment of Contention Window, **DASP** = Dynamic Adjustment of Superframe Sub-Periods, **ABC** = Adjustment of Backoff Counter.

thus, causing congestion and increasing collision. This throttles down the overall network performance regarding PDD, throughput, and energy consumption.

4.3. Under ABPR category – IEEE 802.15.4

PNP-MAC [26] aims to reduce PDD and to raise throughput of heterogeneous traffic types. For this purpose, PNP-MAC assigns distinct BPRs to heterogeneous traffic types; thus, reducing PDD and raising throughput, but insignificantly. However, the BPRs of EA (Emergency Alarm), MC (Medical Continuous), MR (Medical Routine), and NMC (Non-Medical Continuous) are overlapped with each other, resulting congestion. Also, the BPRs for all TCs remain the same in third, fourth, and fifth backoffs; thus, increasing collision and retransmission, which reduces throughput. Further, a long BPR such as 0 – 63 is given to MC & MR traffic types, and 0 – 95 is assigned to NMC and Other traffic types in the last three backoffs; thus, these traffic types face a long delay. So, the aforementioned design limitations of PNP-MAC cause transmission congestion which in result raises PDD and throttles down the throughput of the network. LTA-MAC [97] aims to improve network performance regarding PDD, PDR and EC via contention-based traffic prioritization. LTA-MAC proposes different BPRs for each backoff but only one BPR is proposed for every single backoff. This design slightly improves network performance. Nevertheless, CDP (Critical Data Packet) and ODP (Ordinary Data Packet) get the same BPR in the first backoff. Similarly, CDP and ODP get the same BPR in the second backoff but are distinct from the first backoff and so on. Also, the proposed BPRs for first and second backoffs are very short. Resultantly, increasing collision ratio which reduces network performance in terms of PDD, PDR and EC.

TCP-CSMA/CA [98] targets to upgrade PDD, throughput, PDR and EC using contention-based traffic prioritization. TCP-CSMA/CA assigns distinct, moderate, and prioritized BPRs to each traffic class in every backoff which notably enhance PDD, throughput, PDR, and EC. Conversely, the computation of a distinct BPR for each TC in every backoff poses a computational overhead on BMSNs [125], which raises energy consumption and PDD. It also reduces throughput. The objective of eTA-MAC [99] is to improve throughput, PDD and EC via packet's lifetime control mechanism and contention-based traffic prioritization. eTA-MAC assigns distinct, moderate, and prioritized BPRs to all traffic types in every backoff with the dynamic adjustment of emergency traffic and packet's lifetime management which significantly enhances throughput, PDD and EC. However, the channel conditions are not considered while computing the lifetime of emergency and non-emergency data packets. Therefore, majority of data packets may expire before reaching the destination in worst channel conditions.

4.4. Under ACW category – IEEE 802.15.4

PDM scheme [120] also focuses on-time delivery of high priority data packets with least possible delay by introducing priority toing and frame tailoring techniques. Urgent data packets are delivered on-time by performing single CCA but also face little bit delivery delay because of their frame length adjustment [123]. CoR-MAC [121] intends to improve channel utilization via contention-based prioritization and dual channel reservation. The reserved timeslots for different traffic types reduce their packet delivery delay but increasing number of urgent packets which reserve more timeslots on priority basis results in delaying the transmission of non-urgent data packets.

4.5. Under DASP category – IEEE 802.15.4

PTA scheme [122] targets to improve quality of service for different traffic types. The CAP is divided into multiple phases and traffic types are distributed among these phases for prioritized data transmission. Besides, traffic types are not prioritized in phase II and III; thus, delaying the lower priority traffics. As a result, energy consumption is increased, and throughput is decreased. PA-MAC [114] aims to reduce energy consumption and contention complexity among heterogeneous traffic types. For this purpose, it distributes the CAP into multiple phases and also, allots various traffic types in these phases. This approach improves throughput and also, reduces energy consumption to some extent but the traffic types bounded to phases 2, 3 and 4 still face congestion due to competition during channel access. Thus, affecting overall network performance regarding delay, throughput, and energy consumption.

4.6. Under DASP category – IEEE 802.15.6

Similar to PA-MAC, PCA-MAC [81] also aims to reduce contention complexity through graded channel access during the CAP. However, a phase-level prioritization mechanism is not provided during contended channel access in the CAP; thus, all traffic types simultaneously contend for channel access during the superframe's 2nd, 3rd, and 4th sub-phases. As a result, traffic is delayed and more energy is consumed.

4.7. Under ACW category – IEEE 802.15.6

MDTA-MAC [89] targets to minimize delivery delay and energy consumption by using traffic prioritization. A distinct contention window is given to each traffic type to reduce delay and to raise PDR. Besides, the EAP phase requires more slots for the transmission of emergency traffic in emergency situation. Thus, the length of the EAP phase is increased accordingly, which reduces the transmission opportunity of non-emergency RP and OP traffic. Therefore, BMSNs with RP or OP traffic consume more energy due to high PDD. Further, the repetitive assignment of BCRs to various traffic types in the 1st backoff remain unchanged in 2nd, 3rd, and 4th backoffs; thus, increasing contention complexity which increases collision and thus, throttling down network performance regarding PDD, PDR, and energy consumption. NOBA [92] aims to reduce collision rate among different priority traffic classes. Therefore, a distinct CW is given to various traffic classes in every backoff which little bit reduces the delay and improves the throughput. But the given BCR remains unchanged during 1st and 2nd, 3rd, and 4th backoffs. Therefore, it causes a high collision, increasing the PDD and energy consumption and reducing throughput. The assigned BCRs are short in range which increases collision rate in case of emergency. Further, the increasing number of SNs in various UPs also throttles down network performance due to the assignment of short BCRs in every backoff.

4.8. Under ABC category – IEEE 802.15.6

PBCR [93] intends to achieve lower delay and high throughput by using parametric backoff counter. The user priority based parametric values uniquely improve network performance, but a computational overhead is imposed on SNs because of PBCR calculation in every backoff. Further, a high value is generated for BC which exceeds $CW_{max}[UP]$ in the first backoff. Thus, traffic from all UPs is delayed. Such design limitations affect the network performance regarding delay, throughput, and PDR. BCSP [94] targets to reduce collision ratio, waiting time during idle listening and improve the transmission reliability by enhancing backoff counter selection criteria. However, the normal data can obtain the channel prior to emergency data due to the proposed backoff counter selection criterion. The minimum value of CW is selected from the undefined range for high and normal priority data types. Therefore, high, and normal UPs sensor nodes can access the channel before sensor nodes have emergency traffic. Thus, any UP-SN can access the channel before any other UP-SN, increasing contention complexity. This contention complexity raises collision, increasing PDD and decreasing throughput and PDR.

5. Open issues and research challenges

The above discussion clearly shows that, although adequate research is going on, still many open issues and research challenges exist. Open issues and research challenges of contention-based traffic prioritization against IEEE 802.15.4 and IEEE 802.15.6 MAC are given below:

The existing contention-based traffic priority MAC protocols (i.e., using slotted-CSMA/CA of IEEE 802.15.4 standard) prioritize traffic either through the adjustment of BE and CW, adjustment of BE only, introducing various BPRs, adjustment of CW only, or via dynamic adjustment of superframe sub-periods. However, adjustment of only CW is not enough because heterogeneous-natured BMSNs allocate the channel before packets transmission. Therefore, if not prioritize during the contended channel access then not possible to reduce packet delivery delay. Actually, CW is used to avoid collision between transmitted and ACK packet. In addition, it prohibits the transmission of data packets from more than one BMSNs at once on the same channel to avoid collision. Hence, the appropriate adjustment of BE and CW values for heterogeneous natured-BMSNs generating traffic with various degrees of importance, is an open research challenge for future contention-based traffic priority MAC protocols. The alternative contention-based traffic prioritization solution that is introducing various BPRs causes traffic congestion. Firstly, if the same BPR is given to the different traffic classes. Secondly, when a distinct BPR is given to every traffic class in the 1st backoff but ramians same in all backoffs. Thirdly, if a distinct BPR is provided to each traffic class in every backoff but BPR is not designed moderately. Thus, designing the moderate BPRs for different traffic classes in every backoff is another research challenge because it improves network performance regarding PDD, PDR, throughput, and energy consumption. On the other hand, the contention-based traffic prioritization solution via dynamic adjustment of superframe sub-periods also have some opens issues and research challenges. Although, existing traffic priority MAC protocols divide superframe in multiple sub-periods based on traffic prioritization but does not provide any sub-period-level prioritization mechanism. Thus, sub-period-level traffic types contend simultaneously for channel access which results in a collision among packets of various traffic classes, thus, delaying the overall traffic.

Further, the existing contention-based traffic priority MAC protocols (i.e., using slotted-CSMA/CA of IEEE 802.15.6 standard) prioritize traffic either through the dynamic adjustment of superframe sub-periods, adjustment of CW, or the adjustment of BC. Similarly, as discussed earlier, the sub-periods level prioritization is not provided for BMSNs belonging to different priority classes in case of superframe sub-periods dynamic adjustment. Thus, sub-periods level traffic prioritization is an open research challenge. Another open issue and research challenge is to design a balanced CW size because the short CW ranges raise the collision if higher priority BMSN's packet generation rate increases due to emergency. Further, the assignment of short CW ranges in each backoff also reduces network performance when the number of BMSNs is increased in various traffic classes. In short, the design of contention-based traffic prioritization for traffic priority MAC protocols in WBANs is a challenging job.

6. Conclusion

WBAN is a technology that provides early detection, prevention, and continuous patient monitoring. It can manage future health problems and minimize health care costs. In WBANs, the MAC protocols design is a challenging job due to the unique constraints. This research article discusses the issues of contention-based traffic prioritization at the MAC layer in WBANs. Then a comprehensive study of existing contention-based traffic priority MAC protocols in WBANs is provided. Each MAC protocol is critically analyzed to find its strengths and limitations. The existing contention-based traffic priority MAC protocols in WBANs consider various issues, but still, much research is required. The current contention-based traffic priority MAC protocols provide distinct BPRs for every backoff but do not provide distinct BPR to each TC at the backoff level. Moreover, those which provide distinct BPRs to each TC use the BPR of high priority TC as a subset in the BPRs of low priority TCs. In addition, some of them assign discrete BPRs to every TC in the first backoff, but the given BPRs remain unchanged until the last backoff. A few assign distinct BPRs to each TC in every backoff, but they do not prioritize CW. Some prioritize CW but do not assign distinct BPRs to various TCs. Some of them assign distinct BPRs to each TC in every backoff and prioritize CW but have some limitations in CW prioritization. Finally, open issues and research challenges are discussed based on slotted-CSMA/CA of IEEE 802.15.4 and IEEE 802.15.6 standards.

CRediT authorship contribution statement

Farhan Masud: Conceptualization, Methodology, Software, Writing – original draft. **Gaddafi Abdul-Salaam:** Project administration, Investigation, Writing – review & editing. **Muhammad Anwar:** Visualization, Investigation, Resources, Writing – review & editing. **Abdelzahir Abdelmaboud:** Validation, Formal analysis, Writing – review & editing. **Muhammad Sheraz Arshad Malik:** Data curation, Writing – review & editing. **Hadhrami Bin Ab Ghani:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through large group Research Project under grant number (RGP.2/175/44).

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