Toward 3GPP Sidelink-Based Millimeter Wave Wireless Personal Area Network for Out-of-Coverage Scenarios

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***Abstract*—With advancements in distributed autonomous systems (e.g., vehicles, sensors, and robots) in the 5G/6G era, sidelink communication technology has evolved as a distributed communication system in the third-generation partnership project (3GPP). However, the current sidelink communication design focusing on information dissemination or point-to-point communication with a low rate is not suitable for rapid development of such autonomous systems. Instead, based on sidelink, developing distributed wireless personal area networks (WPANs) with a drastically higher rate for transmitting user data is essential. The overarching goal of this study is to explore the possibility of sidelink communication evolution to 1) form a distributed and autonomous WPAN and 2) support millimeter wave (mmWave) bands. Our core idea is to merge several design concepts of the precedented mmWave WPAN standards, i.e., IEEE 802.15.3c/11ad, into the sidelink communications, thereby bridging the gap between the two separated systems. This article presents the anatomy of the IEEE 802.15.3c/11ad system with a focus on the formation of mmWave WPANs among distributed nodes and their operation. In addition, the current status of sidelink communication system design is highlighted, along with the missing building blocks, which are required to develop 3GPP sidelink-based mmWave WPAN systems. Simulation results shed light on merging IEEE 802.15.3c/11ad concepts into 3GPP sidelink communication regarding a control data transmission scheme, which should be designed to enhance robustness and is a crucial step for subsequent high-rate user data transmission.**

***Index Terms*—5G new radio (NR), IEEE 802, millimeter wave (mmWave) communication, sidelink, wireless personal area network (WPAN).**

I. Introduction

A. Background

THE ONGOING deployment of fifth-generation (5G) mobile networks has sparked interest in connecting an extreme number of nodes in distributed autonomous systems (e.g., vehicles, sensors, robots, and peripheral wearables) with digital worlds in the Internet to overcome social challenges in the physical world [1], [2], [3], [4]. However, to realize this futuristic goal, unprecedented challenges in designing wireless communication systems that support extremely high rates, massive connectivity, ultrareliability, and low latency for 5G or sixth-generation (6G) communication systems need to be addressed [5], [6]. Therein, considering the joint challenges of managing the boosting user traffic [7] and meeting the stringent requirements for the rate, low latency, and reliability, the current centralized cellular network designs and cloud-based software designs fall short of supporting upcoming distributed autonomous systems. Instead, as discussed by Harada et al. [8] and Agha et al. [9], beyond 5G and 6G communications should also support a distributed network, where closely separated nodes create a wireless network in a distributed manner without requiring a centralized base station (BS). This transformation paves the way to reaching an extremely high-rate and fulfill the stringent requirements of low latency and reliability. Accordingly, upcoming distributed autonomous system designs, such as autonomous vehicles, unmanned aerial vehicle (UAV) operations, and connected robotics, are expected to be designed based on the distributed wireless networks.

The third-generation partnership project (3GPP) is not overlooking this challenge; rather, developing sidelink communication with a special focus on vehicle-to-everything (V2X) communication [10], [11], [12], [13], [14]. Sidelink is a direct point-to-point communication design between user equipments (UEs) without involving BSs and is constructed over an air-interface compatible with that of 3GPP cellular systems. Sidelink communication dates back to Release 12 [15], [16] in the long-term evolution (LTE) system, wherein the first version of sidelink communication was established as a means of device-to-device communication mainly for public safety (e.g., emergency calls and discovery of incidents outside the coverage of a BS) and other commercial applications [15]. Subsequently, the 3GPP established a specification for LTE V2X under Release 14 for basic safety applications [17] and added more functionalities, such as repeated transmission and collision-avoidance mechanisms for distributed resource management, to enhance reliability [18]. In LTE V2X, the operational band corresponds to that of an intelligent transport system (5.9 GHz), and this design principle is followed by 5G new radio (NR) sidelink communication, which primarily facilitate V2X communication. The 5G NR sidelink involves more operating bands, including licensed/unlicensed bands,

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and exhibits more functionality to support advanced safety applications and even autonomous driving systems, such as Quality-of-Service (QoS)-aware transmission [19], physical (PHY) layer hybrid automatic repeat request [20], and allows departure from broadcast transmission for unicast and groupcast communications [10], [19].

The 5G NR-based sidelink communication is partially supportive of autonomous vehicles without involving any BSs. However, the current focus of sidelink on supporting only information dissemination or point-to-point communication with a simplified protocol hardly allows us to envision and design entire autonomous distributed systems for upcoming applications. For autonomous distributed systems, one may be attracted to construct a high-rate wireless personal area network (WPAN) with the 5G NR air interface, where the communicating nodes are personal peripherals on desks/conference rooms, cooperative UAVs for monitoring, or robots for smart factories. Therein, the communicating nodes must immediately form an ad hoc WPAN and transmit a large amount of streaming data, locally exchange a large amount of sensory data, or transmit even machine-learning model parameters for control [21]. To support such upcoming autonomous systems with a 5G NR interface, the current sidelink communication ought to depart from information dissemination or point-to-point communication for distributed wireless networking systems with drastic rate enhancements and leverage even higher frequency bands, i.e., the millimeter wave (mmWave) frequency band. The present study was conducted to assess the possibility of designing 3GPP sidelink-based distributed mmWave WPAN systems that can operate under the out-of-coverage scenario of any BSs. The significance and motivation for this study are explained in detail in the following section.

B. Significance, Motivation, and Challenge for Sidelink-Based Distributed mmWave Wireless Personal Area Network

1) Gap Analysis Between mmWave WPAN and 5G NR Sidelink Communications: To date, tremendous efforts have been devoted to establishing technical specifications for distributed mmWave WPANs, which operate mainly in the 60 GHz band. The IEEE standardization task groups IEEE 802.15.3c [22], [23], [24], [25], [26], and IEEE 802.11ad [27], [28], [29], [30], [31], which are briefly summarized as follows:

IEEE 802.15.3c: IEEE 802.15.3c was one of the world's first task groups established to define distributed mmWave WPAN systems in the mid-2000s with the aim to commercialize mmWave WPAN systems. The defined WPAN is termed a piconet, and the target application is a high-speed wireless network formed by proximity nodes, such as the network among personal desktop peripherals and point-to-point connectivity for kiosk downloading. The targeted communication distance was less than 10 m [23].

IEEE 802.11ad: IEEE 802.11ad was established to define both mmWave wireless local area network (WLAN) and IEEE 802.15.3c-like WPAN systems. The WPAN is called a personal basic service set (PBSS) [38], whose targeted use cases are similar to those of IEEE 802.15.3c (e.g., connectivity among personal peripherals and kiosk downloads). In addition, IEEE 802.11ad established a technical specification compatible with IEEE 802-based WLANs, wherein an access point (AP) serves as an infrastructure BSS. The targeted communication distance was several tens of meters, according to the evaluation methodology [39].

While more detailed design principles of the IEEE 802.15.3/11-based mmWave WPANs are presented in Section II, mmWave WPANs are characterized by the following objective:

Without coordination of any BSs, two or more communication nodes form a community leveraging a mmWave wireless communication link and are configured to reach and communicate with almost every member node on the network layer.

As the name suggests, mmWave WPAN is referred to as a community of wireless nodes where each member node is periodically informed of the existence of member nodes via their medium access control (MAC) and Internet protocol addresses, and almost every pair of member nodes can deliver data packet for each other on the network layer. Forming such a network ensures that as shown in Fig. 1(a), a member node can perform an on-demand access to almost every membership node, thereby enabling a flexible and reliable data exchange among the nodes in distributed autonomous systems. The potential advantages of the mmWave WPAN are elaborated on in the next section.

In contrast to mmWave WPANs, the current 5G NR sidelink lacks such flexibility. The 5G NR sidelink defined the following three communication modes: 1) broadcast communication; 2) groupcast communication; and 3) unicast communication [10], where the usage of mmWave bands is currently considered [41]. However, the former two communication modes are intended for information dissemination and do not establish a network connection. Hence, these two communication nodes cannot perform a packet delivery for a specific receiver node as shown in Figs. 1(b) and (c). The last unicast communication can perform a packet delivery for a specific receiver node. However, as shown in Fig. 1(d), the unicast communication is intended to perform a point-to-point communication; hence, the unicast communication cannot form a mmWave WPAN in the above sense. To summarize, the 5G NR sidelink is designed to initiate user data transmission for proximity nodes as immediately as possible, which cannot configure more than two communication nodes so that every pair of nodes is allowed to communicate with each other.

2) Motivation for 5G NR Sidelink-Based mmWave WPAN and More Dedicated Protocol to Manage Network: As detailed in the previous section and shown in Fig. 1, mmWave WPAN has been designed to allow a network layer to establish pervasive connectivity among nodes while the sidelink communication was designed to initiate packet delivery for arbitrary proximity nodes as immediately as possible. The former entails a more dedicated MAC protocol to initiate and maintain the network (e.g., initial access procedure and multiple access procedure) while the latter entails a more simplified protocol. Hence, to design 5G NR sidelink-based mmWave WPAN, we should bring the dedicated MAC protocol into the already-simplified sidelink communication

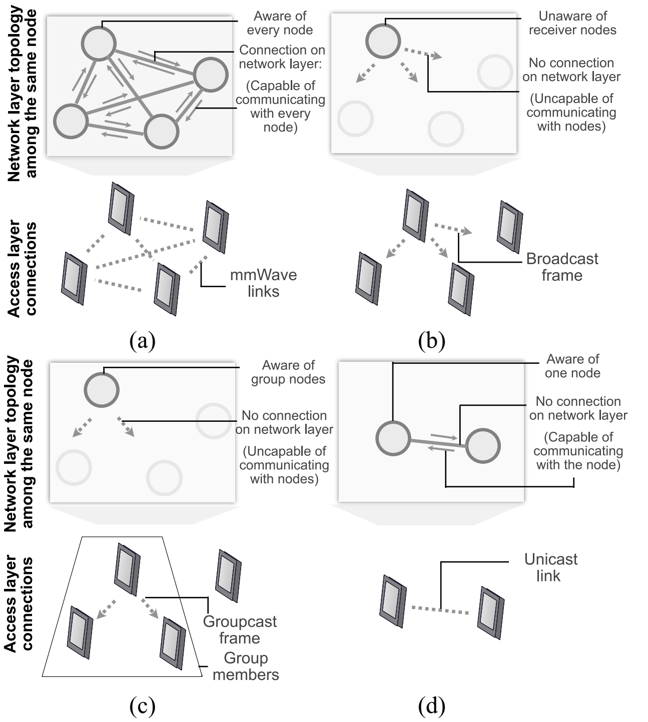

Fig. 1. Overview of mmWave WPAN and sidelink communication with their network layer link topology. (a) mmWave WPAN. (b) Sidelink broadcast communication. (c) Sidelink groupcast communication. (d) Sidelink unicast communication.

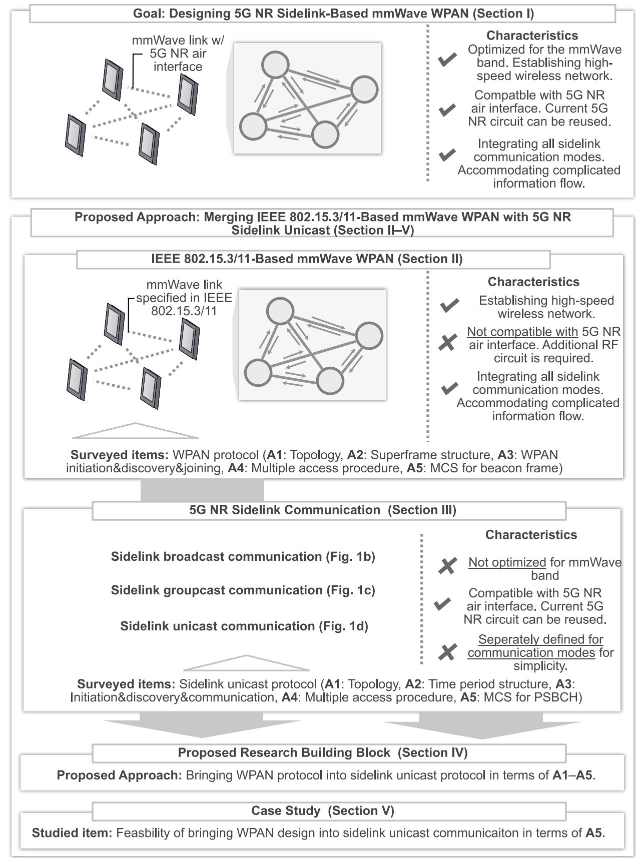

Fig. 2. Overview of this article and roadmap toward 3GPP sidelink-based mmWave WPAN with a 5G air interface.

protocol, which may counteract the initial objective of the 5G NR sidelink.

Nonetheless, the 5G NR sidelink-based mmWave WPAN is worth considering for the following two advantages. First, as is found in Fig. 1 by viewing the node relationship from the network layer, the mmWave WPAN integrates all of the aforementioned three sidelink communication modes. More concretely, once a mmWave WPAN is established, each member node can perform broadcast, groupcast, and unicast communications with every receiver node. This can be interpreted as an integration of separately defined sidelink communication modes, where a destination for a data packet can be more flexibly determined than the 5G NR sidelink. Thus, the 5G NR sidelink-based mmWave WPAN can accommodate a more complicated information flow among nodes with a high rate, which is beneficial for developing more intelligent and sophisticated autonomous distributed systems.

Second, envisioning a long-term future, 5G NR sidelink-based mmWave WPANs exhibit the paramount potential to underpin a large-scale distributed wireless network run by a massive number of distributed nodes, which has recently been proposed as an alternative networking platform without the need for the current Internet [8], [9], [42]. In this type of network (termed "virtual community network" in [8] and "horizontal 6G network" in [9]), a large number of nodes run a huge Internet-like network, which totally relies on wireless connectivity. Moreover, the nodes construct a local overlaid network virtually, and reaching remote servers or any remote routers is no longer needed to run its application if nodes/servers are located close to each other, contributing to drastically reducing traffic load in the current Internet. For this vision, creating a network topology as illustrated in Fig. 1(a), not solely relying on the current simplified 5G NR sidelink communication modes, is required, which is analogous from the fact that the current Internet possesses such a pervasive topology. Hence, merging sidelink communication with the concept of mmWave WPANs mainly standardized in IEEE 802.15.3/11 is of paramount importance for investing in a paradigm shift for the notion of futuristic connectivity.

3) Challenges: To this end, the following critical question remains: How can we define a concrete protocol to successfully allow 5G nodes to form an mmWave or even terahertz WPAN in a distributed manner based on sidelink communication with the 5G NR air interface? On the one hand, the current sidelink communication does not define any strategies to define a protocol to form a WPAN. On the other hand, the aforementioned IEEE 802-based mmWave systems were developed outside the 3GPP standardization activities and are not applicable to the 5G NR interface. These two challenges are significant obstacles because a drastic transformation of the system design may be required to support mmWaves in terms of the PHY layer and MAC layer protocol for sidelink. This mismatch between the air interface and design principles represents a serious challenge that should be addressed.

C. Contributions, Scope, and Paper Organization

Motivated by the aforementioned challenges, this study explores the possibility of developing 3GPP sidelink-based mmWave WPAN systems. The proposed roadmap is illustrated in Fig. 2 and is embodied in this article. The principles provided in this article are: 1) learning from the existing IEEE 802-based mmWave WPAN system; 2) learning the current sidelink communication design; and 3) merging mandatory concepts into sidelink communication to suit the 5G NR interface. Provided this roadmap, this study fills the profound gaps between IEEE 802-based mmWave WPANs and 3GPP sidelink communication, thereby aiming to shed light on the methodology to form a mmWave WPAN by sidelink communication with a 5G NR interface outside the coverage of any BSs. The contributions of this article are as follows:

First, this article summarizes the landmark IEEE 802-based mmWave WPAN systems, that is, IEEE 802.15.3c and IEEE 802.11ad, focusing on how mmWave WPAN can be formed by distributed nodes in Section II. The unique feature of this survey is its special and consistent focus on the MAC procedures for initiating, joining, and communicating within mmWave WPANs. Moreover, while focusing on this perspective, we highlight the clear affinity that lies between IEEE 802.15.3c and IEEE 802.11ad, which could be cast as the key design concept for the successful operation of mmWave WPANs among distributed nodes. To the best of our knowledge, this perspective has not been provided in the literature, although numerous studies on IEEE 802-based mmWave WPAN systems have been conducted to date [23], [24], [25], [26], [28], [29], [30], [31], [33], [34], [35], [37], [43]. This is because the existing papers may summarize *each* standardization and not provide the outlook found by comparing the existing standardized mmWave WPAN systems. Only one book [44] provided several standardized mmWave WPAN systems, including IEEE 802.15.3c and IEEE 802.11ad; however, this book focused mainly on PHY layer perspectives and did not fully provide MAC procedures to form and operate mmWave WPANs.

Second, this article summarizes the current sidelink communication, focusing on the protocol to establish sidelink communication without the need for any BSs in Section III, based on which we provide a comparative analysis between IEEE 802-based mmWave WPANs and sidelink communications in terms of MAC procedures. Despite the difference, we found an affinity between them in terms of topology and other MAC signaling perspectives, which provide the starting point to tackle the challenge of integrating the key concepts of the IEEE 802-based mmWave WPAN into sidelink communications. Based on this discussion, we proceed with itemizing the key research building blocks that lead to successful integration in Section IV. Moreover, in addition to integration, we propose principal research items to evolve the resultant sidelink-based mmWave WPANs into futuristic autonomous and distributed systems.

Finally, to confirm the above hypothesis, this article provides a motivating case study to integrate the concept of IEEE 802-based mmWave WPANs into sidelink communication, focusing on signaling to form an mmWave WPAN in Section V. In more concrete, as will be shown in Section II, while forming an mmWave WPAN, a node uses a robust broadcast frame termed common mode signaling (CMS), which exhibits a packet error rate (PER) of 10^{-1} even under a low-signal-to-noise ratio (SNR), that is, -12 dB. This design concept should be passed into sidelink communication. However, the broadcast frames for signaling in sidelink communication, termed the physical sidelink broadcast channel (PSBCH), have been shown to fall short of such robustness. We propose an enhanced PSBCH oriented to form an mmWave WPAN. The simulation results demonstrate that the enhanced PSBCH outperforms not only the original PSBCH but also IEEE 802.15.3c common-mode signaling in terms of both robustness and data rate. These results highlight the feasibility of the above concept to integrate precedent mmWave WPAN designs into sidelink communications and extend beyond precedent mmWave WPAN systems.

A list of abbreviations is attached at the end of this article. Readers are encouraged to refer to this while proceeding with this article as Table II.

II. Review of IEEE 802-Based WPAN and MAC Design Principles

For distributed mmWave WPAN systems, task groups inside the IEEE 802 standardization communities have put tremendous effort into defining the PHY and MAC layer techniques to form a network, while carefully considering the unique challenges incurred by the usage of mmWave bands. Evaluating these techniques is beneficial because of the architecture and protocols for the formation of sidelink-based distributed autonomous mmWave WPAN systems. Hence, we describe the MAC layer techniques defined by the IEEE 802 standardization task groups for 60 GHz mmWave networks, IEEE 802.15.3c [22] and IEEE 802.11ad [27], with particular focus on how distributed nodes can autonomously form an mmWave network and communicate with another node inside the network.

Notably, instead of surveying all the standardized protocols in the above task groups, we survey only the key aspects related to network perspectives and other MAC functionalities in standard mmWave WPANs. The key aspects related to these networks are examined based on information about (Q1) what types of networks are formed, (Q2) how a mmWave WPAN is formed in a distributed manner, and (Q3) what the mechanism underlying the mutual communication of the nodes inside the network is. Hence, we limit the discussion to the following five aspects.

1) *A1:* Topology of the formed network. This serves as the answer to question Q1.
2) *A2:* Superframe structure. This serves as a premise for understanding both Q2 and Q3 in the above standards. A superframe is referred to as a repeated period, wherein the time is segmented to allow multiple accesses inside the network. This time division is applied to all standards; hence, understanding this structure is important for discussing procedures A3 and A4.

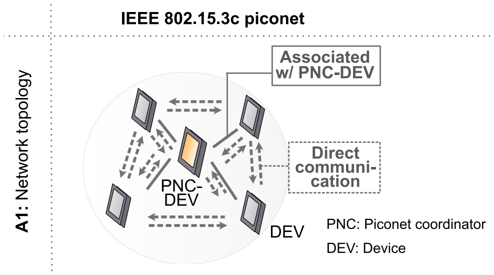

Fig. 3. A1: Topology in IEEE 802.15.3c piconet.

3) *A3:* Procedures for initiating, discovering, and joining a network. This serves as an answer to question Q2.
4) *A4:* Multiple access methods inside the network. This serves as a concrete answer to question Q3.
5) *A5:* The modulation and coding scheme (MCS) of beacon signals, which is related to all the procedures required to start, discover, and join a network. This serves as a supporting technique to realize the network formation, and hence, is related to Q2.

A. IEEE 802.15.3c Piconet

A1 (Topology): In the IEEE 802.15.3c standard, communication nodes termed "devices (DEVs)" form a personal network termed "piconet," which is compliant with the precedent IEEE 802.15.3 WPAN system [45] which operates at 2.4 GHz. The topology is illustrated in Fig. 3. One DEV starts a piconet and manages the membership status, network synchronization, and resource allocation in a centralized manner, which is called a piconet coordinator (PNC). Other DEVs search for and are associated with the PNC, thereby joining the piconet. In a piconet, DEVs can communicate with not only the PNC but also another DEV inside the piconet with the help of the PNC, allocating a contention-based or contention-free time resource for the DEV-DEV communication. In summary, the piconet exhibits a star topology, and exceptionally, direct communication between nodes is allowed.

A2 (Superframe Structure): Fig. 4 shows the superframe structure in IEEE 802.15.3 c. The time periods in a superframe are categorized into beacon, contention access period (CAP), and channel time allocation period (CTAP). During the beacon period, the PNC broadcasts a beacon frame to allow DEVs to discover the PNC, synchronize with the PNC, and be aware of information elements related to network management (e.g., start and end times of each CAP and CTAP [22]); hence, the beacon period plays a critical role in forming an mmWave WPAN. As a specific technique to mmWave communications, the PNC can disseminate multiple beacon frames in all directions during the beacon period using a quasi-omnidirectional antenna (i.e., a type of directional antenna) in a time-division manner. This option plays a crucial role in expanding the coverage area of the piconet.

CAPs are primarily used by the PNC to receive association request commands or other control commands transmitted by other DEVs.[1] In CAPs, DEVs perform carrier-sense multiple

[1]Besides control frames, the DEVs can also transmit asynchronous user data [22]. The allowed data type is indicated as a piconet synchronization parameter field in beacon frames.

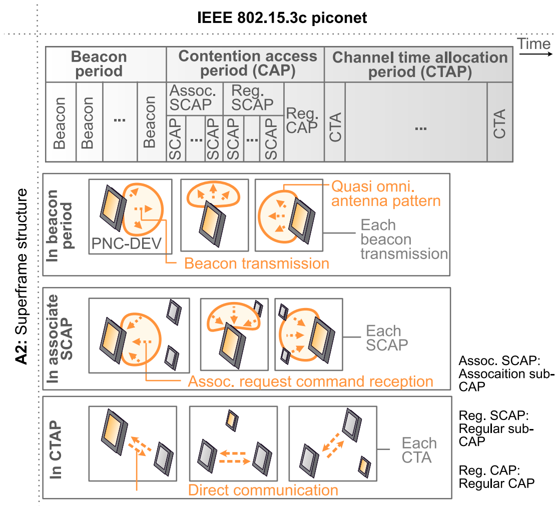

Fig. 4. A2: Superframe structure in IEEE 802.15.3c piconet.

access with a collision avoidance (CSMA/CA) procedure to avoid collisions among the DEVs. As the PNC accepts an association request command, DEVs that have not yet joined the piconet can also perform frame transmission. As a specific characteristic of mmWave-based WPAN, the IEEE 802.15.3c defined a directional CAP as shown in Fig. 4 [22]. The directional CAP is divided into several sub-CAPs (SCAPs), and the PNC listens to a transmitted frame with a specific quasi-omnidirectional antenna. Among the different SCAPs, PNC uses different quasi-omnidirectional patterns, thereby covering all directions. This method also leads to an expanded coverage area owing to an enhanced receiver antenna gain. Notably, directional CAP is repeated twice in a superframe; the first directional CAP accepts association request commands and is named "association SCAP," while the second one accepts other control commands and is named "regular SCAP." The regular SCAP is followed by a basic CAP without directional reception and is called "regular CAP."

In the CTAP, DEVs allow data transmission to other DEVs in a piconet. During this period, all transmissions are performed based on the time division multiple access (TDMA), and each time period, called channel time allocation (CTA), is dynamically allocated by the PNC according to a request submitted by the DEVs. In addition, a PNC can allocate a CTA to a specific pair of DEVs in a fixed location in every superframe to allow for isochronous data transmission [45]. Optionally, CTAP is also used to exchange command frames; in this case, slotted ALOHA-based collision avoidance is performed exceptionally [45].

A3 (Procedures to Initiate and Join Network): Because the network is based on a star topology coordinated by the PNC, the network initiator is a DEV capable of being a PNC. The detailed network initialization procedure is shown in Fig. 5. First, a PNC-capable DEV scans all available channels and determines the channel with the least amount of interference [45]. Subsequently, the PNC-capable DEV scans the channel again for a predetermined duration, termed as mMinChannelScan, which issues a beacon frame and starts the network if the channel is idle for that duration. As discussed in the superframe structure section, the beacon frame can be

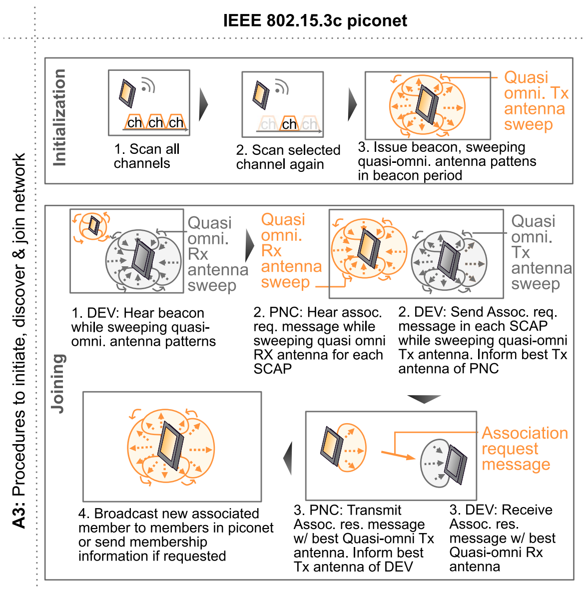

Fig. 5. A3: Procedures to initiate and join the network for IEEE 802.15.3c piconet.

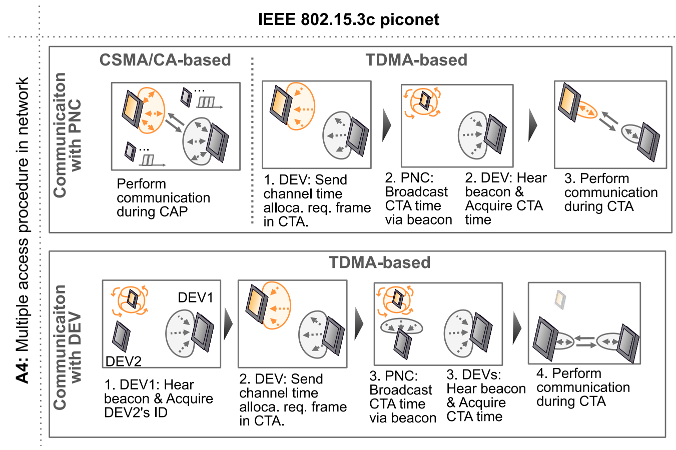

Fig. 6. A4: Multiple access procedure in network for IEEE 802.15.3c piconet.

sent multiple times by sweeping quasi-omnidirectional antenna patterns.

To join a piconet, a DEV performs an association procedure with the PNC using quasi-omnidirectional antennas [22], [46], which is shown in Fig. 5. First, the DEV overhears the beacon and acquires piconet information. To support quasi-omnidirectional receiver antennas, IEEE 802.15.3c allows DEVs to overhear beacons while sweeping quasi-omnidirectional antenna patterns, thereby determining the best receiver antenna pattern. Moreover, in this phase, the DEV can determine the best quasi-omnidirectional transmit antenna pattern for the PNC; hence, the DEV prepares to inform the PNC of the best transmitter antenna pattern in the next phase.

Subsequently, the DEVs send an association request command frame to the PNC in the association SCAP. In this phase, the DEVs do not know the best quasi-omnidirectional transmit antenna pattern; hence, they transmit multiple association request command frames in a SCAP while sweeping its quasi-omnidirectional transmit antenna patterns. These transmissions of the association request messages are repeated for each SCAP period in association with the SCAP, meaning that the PNC searches for association request messages while sweeping its quasi-omnidirectional receiver antenna patterns. This is because the PNC does not know the best quasi-omnidirectional receiver antenna pattern, and it is necessary to search for it. In this phase, the DEV informs the PNC of the best quasi-omnidirectional transmission antenna pattern through an association request message. At this point, the PNC knows the best quasi-omnidirectional transmit and receive antenna patterns, whereas the DEV knows only the best quasi-omnidirectional receive antenna pattern.

In the third step, PNC transmits an association-response message to the DEV with the best quasi-omnidirectional transmission antenna. In the association response message, the ID of the best quasi-omnidirectional transmit antenna pattern of the DEV is included; therefore, the DEV can find the best quasi-omnidirectional transmit antenna pattern. At this point, the alignment of the quasi-omnidirectional receive/transmit antenna patterns on both sides is completed.

Finally, in the fourth step, the PNC broadcasts the status of the newly associated DEV using subsequent beacon frames. At this point, the DEV of interest is a member of the piconet.

A4 (Multiple Access Procedure in Network): The DEVs associated with the PNC can initiate data communication not only to the PNC, but also to another DEV in the piconet. To communicate data with PNC, the DEV can leverage both CSMA/CA and TDMA. The former method is performed during CAP and sends data frames, whereas the latter method is performed to send both asynchronous and isochronous data frames.

The procedure for starting TDMA-based communication with the PNC is illustrated in Fig. 6. First, a DEV (termed DEV1) interested in performing data communication with the PNC sends a channel time-request frame to the PNC based on CSMA/CA during the CAP. Subsequently, the PNC allocates a CTA to subsequent superframes and broadcasts the start and end times of the allocated CTA via the beacon frame. Finally, DEV1 leverages the allocated CTA and communicates the data with the PNC. During the allocated CTA, the PNC and DEV can perform sector- and beam-level beamforming protocols, as demonstrated in [47], and in this communication mechanism, sharp directional antennas can be leveraged.

To perform data communication with another DEV, both CSMA/CA and TDMA are defined in the IEEE 802.15.3 WPAN standard. However, for mmWave communications, CSMA/CA-based communication between the two DEVs may not be preferable because quasi-omnidirectional beams cannot be aligned in the contention-access-based mechanism. This has been referred to as the "deafness problem" [48] and is elucidated in the next IEEE 802.11ad section. Therefore, we only detail the TDMA-based communication procedure, which was shown to outperform CSMA/CA [49]. As shown in Fig. 6, the communication procedure is almost identical to those for the communication with the PNC with the exception that a DEV should acquire the ID of the DEV to be communicated

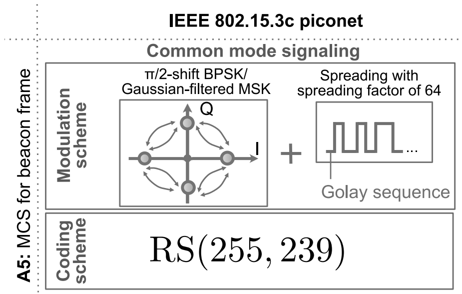

Fig. 7. A5: MCS for beacon frames to coordinate WPAN in IEEE 802.15.3c piconet.

with from a beacon frame.[2] During the communication with the PNC, the two DEVs can perform sector-level and beam-level beamforming protocols, as described in [47] to leverage sharp directional antennas.

A5 (MCS for Beacon): The MCS for broadcast frames, that is, beacon frames, in the IEEE 802.15.3c WPAN is designed to exhibit a low rate to ensure that the control frame reaches the DEVs or PNC against large free-space path losses and other diffraction and penetration losses owing to blockage effects. In particular, for beacon frames, quasi-omnidirectional and nonsharp directional antennas are leveraged in both the PNC and DEVs, wherein the free-space path loss is significant. Hence, designing a low-rate MCS is crucial for realizing the aforementioned network designs A1–A4 [23].

The MCS for the control frame was termed "CMS" and is illustrated in Fig. 7. In the CMS, a single-carrier transmission is defined. As for the modulation scheme, $\pi/2$-shift binary phase-shift keying (BPSK) with spreading was employed. Spreading is performed by multiplying a Golay sequence [22], [50] with a spreading factor of 64 to make it compatible with the preamble sequence, which also uses a Golay sequence for frame synchronization [51], [52] and channel estimation [53]. As a coding scheme, the Reed-Solomon code [54] was applied, considering the hardware complexity at the time of the standardization activity. The codeword length was 255 bytes with a code rate of 239/255.

B. IEEE 802.11ad Personal Basic Service Set

A1 (Topology): The topology of the PBSS in IEEE 802.11ad is structurally similar to the piconet of the IEEE 802.15.3c WPAN as shown in Fig. 8. In PBSS, only one station (STA), termed the PBSS control point (PCP), performs beacon transmission, association,[3] and disassociation. Other STAs are associated with the PCP and communicate with not only the PCP but also other non-PCP STAs. Direct communication between non-PCP STAs is performed with the coordination of the PCP, which is discussed in A4.

[2]A DEV can ask complete information for all DEVs in the piconet by sending a PNC information request command [22].

[3]Technically, the association with the PCP is not mandatory to communicate with a STA in a PBSS [27]; however, without the association, the functionality of the STA is limited. For example, the STA without association cannot request a dynamic grant to the PCP in dynamic scheduling (see A4 in Section II-B) [27], which limits the transmission opportunity and QoS of data frames. Hence, to provide full functionality of IEEE 802.11ad PBSS, we survey only an association-based PBSS, hereinafter.

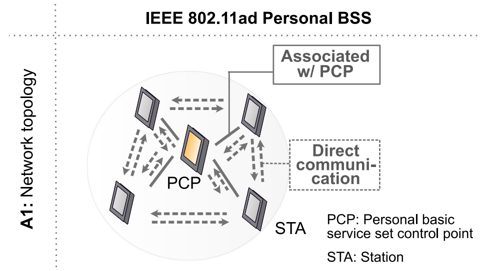

Fig. 8. A1: Topology in IEEE 802.11ad PBSS.

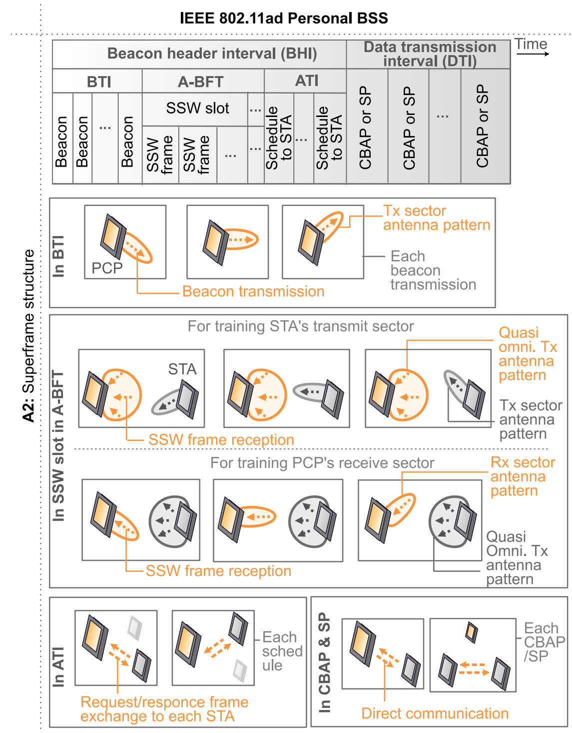

Fig. 9. A2: Superframe structure in IEEE 802.11ad PBSS.

The rationale behind this topology is that the precedent independent BSS (IBSS) structure in the IEEE 802.11 standard [55], which similarly allows peer-to-peer communication between member STAs, is insufficient to support directional communication [38]. In the IBSS, the STAs behave independently such that both the beacons and data frames are transmitted using the CSMA/CA method. This contention-based scheme hinders the alignment of directional antennas prior to peer-to-peer communication, and thus, directional transmission/reception between the STAs is prevented without any treatment [55], [56], [57].[4] Accordingly, the IEEE 802.11ad task group decided that only one STA in the network, that is, the PCP, should be in charge of both transmitting beacons and managing networks with directional transmission/reception of each member STA, so that the member STAs can align the directional antennas to each other prior to direct communication.

[4]This problem does not occur in piconets in the IEEE 802.15.3c WPAN because by default, the directional transmission/reception in the piconets is managed by a PNC by allocating a specific time slot to allow direct communications between nodes.

A2 (Superframe (Beacon Interval) Structure): The superframe structure of the IEEE 802.11ad PBSS is shown in Fig. 9. Notably, the "superframe" interval between beacons is specific to the IEEE 802.15.3 standard, while in the IEEE 802.11, this interval is technically termed as a "beacon interval (BI)" [58]. However, neither interval exhibits significant differences; hence, we consistently refer to the interval as a superframe.

The superframe consists of the following two different parts: 1) beacon header interval (BHI) and 2) data transmission interval (DTI). The BHI is subdivided into three intervals: 1) the beacon transmission interval (BTI); 2) association-beamforming training (A-BFT) interval; and 3) announcement transmission interval (ATI). During the BTI, the PCP broadcasts beacon frames multiple times while sweeping the transmitting antenna sectors. This is because of the following two joint objectives:1) expanding the coverage area of the beacon frames [59] and 2) allowing each STA to determine the best transmit antenna sector of the PCP for the STA. The second process is termed the initiator transmit sector sweep (I-TXSS) and is described in A3.

During A-BFT, beam training is performed using each STA. A-BFT is subdivided into a sector sweep (SSW) slot, in which a PCP exchanges a specialized frame, namely, the SSW frame, for beam training with a typical STA.[5] During A-BFT, one of the following two beam-training processes is performed: 1) training each STA transmit antenna sector, referred to as the responder TXSS (R-TXSS) and 2) training PCP's receiver antenna sector of the PCP, referred to as the responder receiver sector sweep (RXSS). In the R-TXSS, the PCP sets up a quasi-omnidirectional antenna, whereas the STA transmits an SSW frame while sweeping its transmit antenna sectors. In the responder RXSS, an STA transmits an SSW frame with a quasi-omnidirectional antenna, whereas the PCP receives SSW frames while sweeping its receiver antenna sectors. During the ATI, the PCP exchanges requests and response frames for network management with each STA. This period was scheduled by the PCP.

During DTI, pairs of STAs in a PBSS perform data transmission/reception. DTI is divided into several time slots during which limited STAs are allowed for data transmission/reception. Communication in each time slot is performed based on either contention-based access or scheduled time-division multiple access, according to which the time slot is labeled as a contention-based access period (CBAP) or service period (SP), respectively. During CBAP, several STAs may compete for transmission opportunity (TXOP), and to avoid interference, the STAs perform CSMA/CA. Moreover, during SP, a pair of STAs in the PBSS is scheduled for transmission/reception, and the other STAs are not allowed for data transmission.

A3 (Procedures to Initiate, Discover, and Join Network): Similar to the IEEE 802.15.3c piconet, a PBSS is initiated by an STA capable of being a PCP. The detailed procedure is as follows: first, as in the IEEE 802.15.3c piconet, the STA scans all available channels and selects a suitable channel to start the PBSS.[6] As the second step, the STA listens to the selected channel for a predefined duration termed "aMinChannelTime," and if the channel is decided to be suitable to start a PBSS again, the STA commences a PBSS by transmitting directional multigigabit (DMG) beacon frames. This procedure is illustrated in Fig. 10. Notably, the sequence for the Tx antenna sector patterns is randomized at each BI to avoid potential interferences with the beacons transmitted by the other surrounding PCPs [27].

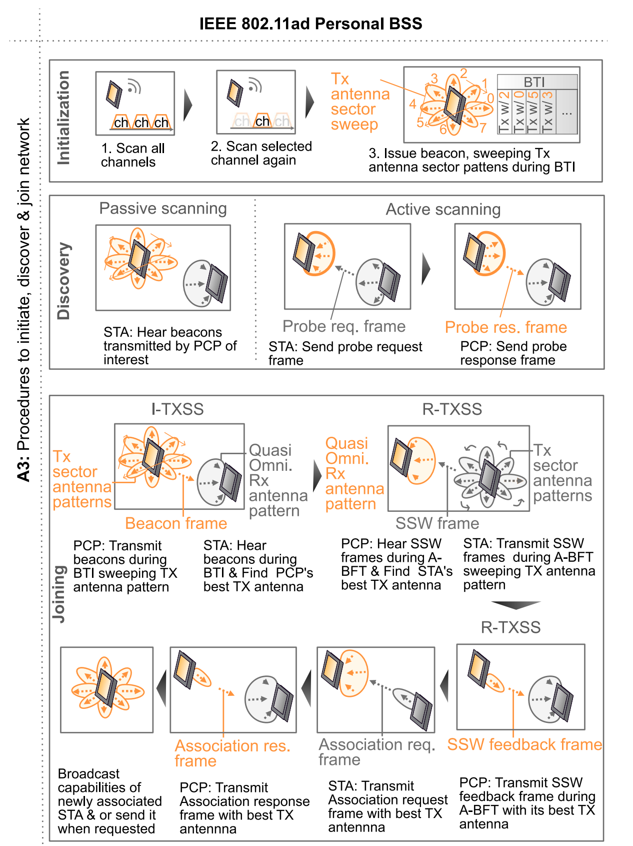

Fig. 10. A3: Procedure to initiate, discover, and joint the network in IEEE 802.11ad PBSS.

To discover the PBSS, IEEE 802.11ad adopts the following two methods: 1) passive scanning and 2) active scanning, as shown in Fig. 10. Passive scanning implies that the STA overhears the channel and detects the beacon frames transmitted by the PCP of interest. During active scanning, the STA sends a frame termed the probe request frame, and the PCP responds to the request by sending a probe response with network information. This procedure can be used to accelerate PBSS discovery because the STA does not need to wait until the reception of a beacon frame.

After the discovery of a PBSS, to join the PBSS, the STA first generally performs beamforming with the PCP within the BTI and A-BFT periods,[7] and then the STA and PCP

[5]The STAs compete with one another to acquire an SSW slot. In the IEEE 802.11ad standard, a backoff procedure is performed to avoid interference.

[6]The methodology of the channel selection is implementation-specific and is not determined concretely by the IEEE 802.11ad standardization.

[7]The beamforming procedure can be continued for subsequent CBAPs or SPs. However, to focus on the procedure to join PBSS, we describe only the beamforming procedure performed during the BTI and A-BFT periods. Moreover, in the subsequent discussion, we describe only the transmit antenna beamforming of the PCP and STA, i.e., initiator transmitter sector sweep

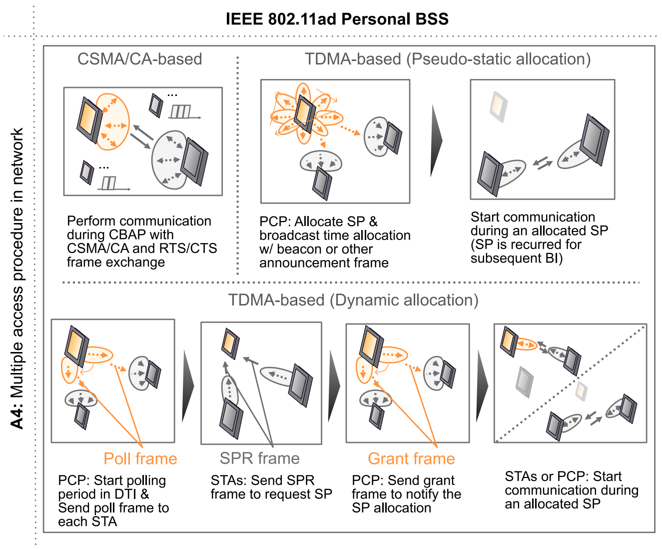

Fig. 11. A4: Multiple access procedure in network for IEEE 802.11ad PBSS.

exchange association request/response frames during the other periods. The beamforming procedure is further divided into two steps: 1) I-TXSS and 2) R-TXSS. The initiator and responder correspond to PCP and STA, respectively. First, the I-TXSS begins when the PCP sends beacon frames multiple times while sweeping its Tx antenna pattern. During I-TXSS, the STA overhears beacon frames with a quasi-omnidirectional receiver antenna and determines the optimal Tx antenna sector ID of the PCP. Subsequently, the R-TXSS is initiated when the STA transmits multiple SSW frames while sweeping the Tx antenna pattern in the A-BFT period, during which the PCP receives the SSW frames with a quasi-omnidirectional receiver antenna. Notably, the SSW frame involves the best TX antenna sector ID of the PCP found in the preceding I-TXSS; therefore, the PCP can determine the best TX antenna pattern for the STA at this point. Subsequently, the PCP immediately sends an SSW feedback message with the best TX antenna pattern to STA to acknowledge the best Tx antenna pattern of the STA. Finally, the STA and PCP exchange the association request and response frames sequentially with their best TX antennas, completing the association. This association occurs during the ATI, CBAP, or SP.

A4 (Multiple Access Procedure in Network): Similar to the IEEE 802.15.3c piconet, IEEE 802.11ad adopts both the contention-based access method and the TDMA method, as shown in Fig. 11. The former type of contention-based access occurs in CBAPs. As the access method, IEEE 802.11ad adopts the distributed coordination function (DCF), which employs CSMA/CA while exchanging request-to-send (RTS)/clear-to-send (CTS) messages to avoid the well-known hidden terminal problem. The protocol is almost the same as that of the IEEE 802.11-based WLAN [58], except that the STAs in the IEEE 802.11ad PBSS are not strictly prohibited from transmitting a frame when the channel is detected as busy. This prompts the simultaneous transmission of multiple-directional STAs that do not interfere with each other, thereby allowing spatial sharing.

In the TDMA method, the PCP schedules the transmission of member STAs by allocating a time slot, that is, an SP, to specific source/destination STAs. IEEE 802.11ad defines the pseudo-static and dynamic allocation of SPs as scheduling methods. In pseudo-static allocation, the SP for a specific source/destination STAs is repeated for superframes with the same location. This allocation method is suitable for isochronous data transmission and must satisfy a constant throughput. For dynamic allocation, as shown in Fig. 11, the PCP first commences a polling period during a DTI, where it transmits a poll frame to each member STA to ask whether each STA demands the allocation of an SP. Subsequently, each STA responds to the PCP by transmitting a service-period request (SPR) frame, thereby requesting an SP. Finally, the PCP allocates SPs to the STAs and issues a grant frame to the STAs before the SPs start. Notably, pseudo-static and dynamic allocations are not exclusive to each other, implying that when dynamic allocation commences, the STA can request pseudo-static allocation from the PCP. A previous study theoretically determined the optimal usage of CBAPs and SPs with respect to the packet arrival rate [60]. The corresponding results demonstrated that this hybrid usage of CBAPs and SPs is more advantageous than the usage of only CBAPs or SPs. Hence, the combination of these two periods was a reasonable choice for enhancing the throughput.

A5 (MCS for Beacon): Similar to the IEEE 802.15.3c piconet, the MCS for the control frames in IEEE 802.11ad was designed to exhibit a low rate to achieve robustness. The MCS is termed as MCS0 or "DMG control PHY" in the IEEE 802.11ad standard.

The DMG control PHY is shown in Fig. 12. The DMG control PHY employs single-carrier transmission. As the modulation scheme, the DMG control PHY employs $\pi/2$-shift BPSK with differential modulation, which is along with spreading with a spreading factor of 32. A Golay sequence with a sequence length of 32 is employed for spreading. As in the IEEE 802.15.3c piconet, the Golay sequence is used because of its compatibility with the preamble sequence for synchronization [61] and channel estimation [62]. For the coding scheme, the DMG control PHY employs a

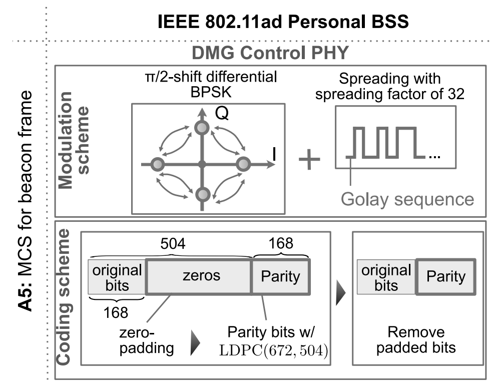

Fig. 12. A5: MCS for beacon frames to coordinate WPAN in IEEE 802.11ad PBSS. The original bits include CRC sequences.

and responder transmitter sector sweep, respectively, although they can also perform beamforming of their receiver antennas in principle. More details on beamforming in IEEE 802.11ad are reported in [27].

low-density parity check (LDPC) code, which is different from the IEEE 802.15.3c common mode that employs the Reed-Solomon code. The code rate is 1/2, which is achieved by padding zeros to each code block with a code rate of 1/3, 3/4 LDPC encoding, and removing the padded bits, as shown in Fig. 12.

C. Summary—Key Principle and Methodology to Operate mmWave WPAN

A summary of the above review is presented in this section, wherein we discuss the common characteristics of the standardized operation of a distributed mmWave WPAN. The aforementioned results show that a distributed mmWave WPAN is characterized by the following characteristics for the above-surveyed items A1–A5.

A1 (Topology): Both the IEEE 802.15.3c piconet and IEEE 802.11ad PBSS exhibit a star topology in which one network coordinator, that is, PNC in the IEEE 802.15.3c piconet and PCP in the IEEE 802.11ad, exists. The network coordinator acts as both a timing source for network synchronization and a central entity that manages time resources by scheduling the transmission of each STA, if necessary. Moreover, member STAs do not only communicate directly with a PNC/PCP, but also communicate with another member STA.

A2 (Superframe Structure): Irrespective of the difference between the IEEE 802.15.3c piconet and the IEEE 802.11ad PBSS in a superframe structure, they exhibited several common features. First, the superframe begins when PNC/PCP transmits multiple beacon frames while sweeping its directional antenna pattern. This is in contrast to a distributed network operating in low-frequency bands, where only one beacon frame is transmitted with an omnidirectional antenna. This directional transmission is crucial because of the expansion of the area in which the beacon frames are reachable. Second, beacon transmission is followed by a specialized period for beam training between the network coordinator and other nodes (i.e., association SCAP in IEEE 802.15.3c and A-BFT in IEEE 802.11ad) so that the member nodes can communicate with the PNC/PCP at least. Third, for the data transmission period, both standards employ separate periods for contention-based access (i.e., CAP in the IEEE 802.15.3c piconet and CBAP in the IEEE 802.11ad PBSS) and scheduled access by PNC/PCP (i.e., CTAP in the IEEE 802.15.3c piconet and SP in the IEEE 802.11ad PBSS).

A3 (Procedures to Initiate, Discover, and Join Network): In both standards, a network coordinator initiates a mmWave WPAN by scanning the channels, searching for a vacant channel, and transmitting multiple beacon frames while sweeping the directional antennas. To discover the network, the nodes in both standards passively scan the channel and find at least one beacon frame transmitted by the network coordinator. While searching for a beacon frame, the discoverer nodes can sweep their directional receiver antennas to enhance the reachability of the beacon frame. Finally, to join the network, the discoverer node and network coordinator perform a beamforming operation to align their respective directional beams. This is because the node and network coordinator must ensure an SNR such that the subsequent association request/response frames are decodable for the network coordinator and discoverer node, respectively. Notably, beamforming in both standards is codebook-based [47], implying that the directional beam is created by a predefined codebook, and the optimal antenna weight vector (AWV) is selected from the codebook with a specified MAC protocol.

A4 (Multiple Access Procedure in Network): Both standards apply a mixed-access procedure for contention-based and scheduled access methods by preparing a dedicated period for either access method in a superframe. Remarkably, the IEEE 802.11ad PBSS also employed the scheduled access method, even though the IEEE 802.11-based WLAN operated in the 2.4/5 GHz bands primarily applied only contention-based access methods. This was motivated by a strong requirement for 1) ensuring QoS for isochronous data transmission (e.g., video streaming and wireless displays) and 2) supporting directional transmission and reception, both of which are well supported by scheduled access methods. Specifically, allocating a time slot for a constant interval ensures a transmission rate that suits isochronous data transmission, as seen in the pseudo-static allocation in A4 for IEEE 802.11ad PBSS. Moreover, scheduled time slots are generally notified to the nodes in the network prior to communication, which facilitates the preparation of a beam alignment in both the transmitter and receiver nodes, as opposed to contention-based access methods. Accordingly, including scheduled access methods, can be considered as a natural requirement for designing distributed autonomous mmWave WPANs.

A5 (MCS for Beacon): Both standards designed a low-rate MCS for transmitting control frames. Both the CMS in IEEE 802.15.3c and DMG control PHY in IEEE 802.11ad exhibit a data rate of approximately 27 Mbit/s, which is significantly lower than that of the other MCSs in the standards that exhibit over 1 Gbit/s. As discussed above, the rationale behind this design is that the control frame should robustly reach the nodes and network controller, even if they do not use highly directional antennas. Both standards apply a hierarchical beamforming protocol, in which low-directional antennas are aligned first and then aligned with highly directional antennas [47], [59]. Therefore, during the transmission of a control frame in the early part of the association, a network controller and node can only apply a low-directional antenna; hence, a low-rate MCS is necessary to reach each other. This idea is naturally included in the design of mmWave WPANs, particularly when the network is a star topology, as detailed in A1.

D. mmWave WPANs Based on Subsequent IEEE 802 Standardization Task Groups

The aforementioned design is followed by subsequent standardization task groups that define mmWave WPAN systems operated in the 60 GHz band. The major task groups were IEEE 802.15.3e and IEEE 802.11ay, which were established after IEEE 802.15.3c and IEEE 802.11ad, respectively. These two standardizations are described in detail below to provide a holistic view of mmWave WPANs.

IEEE 802.15.3e Parinet: The IEEE 802.15.3e task group newly defined a specification for a proximity communication termed "pairnet" operated in the 60 GHz band based on the IEEE 802.15.3 piconet design [36], [37]. The target use cases of the IEEE 802.15.3e pairnets were different from those of the IEEE 802.15.3c piconets. In particular, the IEEE 802.15.3e pairnet targets a communication distance of up to 10 cm [40], which is significantly smaller than that of the IEEE 802.15.3c piconet. Moreover, IEEE 802.15.3e only targets point-to-point communication, in which only a pair of DEVs are involved in a network. Target use cases include Kiosk downloading, ticket gates without placing phones above IC readers, and wireless SD cards, which are promoted by a consortium called TransferJet X [63], [64].

Hence, the IEEE 802.15.3e task group drastically simplified the MAC design [36]. As for topology (A1), the IEEE 802.15.3e pairnet involves only two DEVs, where one is a coordinator termed the pairnet coordinator (PRC), and the other is non-PRC. For the procedures in A3, beamforming for association was not considered, because omnidirectional antennas are sufficient to achieve a satisfactory SNR for the targeted communication range. Accordingly, multiple beacon transmissions in each superframe (A2) are not included [65], [66]. Moreover, after completing the pairing of DEVs, a beacon transmitter, i.e., PRC, ceases beacon transmission because its association with other DEVs is not allowed. This is significantly different from the IEEE 802.15.3c PNC, which keeps transmitting beacon frames for potential DEVs to be associated with. As a multiple access method (A4), the IEEE 802.15.3e pairnet employs neither CSMA/CA protocols nor channel requests for TDMAs. Instead, it employs an alternate transmission procedure between the two DEVs to simplify the multiple access method. In summary, the targeted scenarios and design guidelines differ from those of the target WPANs discussed in Section I-B, and MAC designs were oversimplified for the targeted use cases in this study. Hence, a further survey of this standard was beyond the scope of this study.

IEEE 802.11ay PBSS: Moreover, the design of the IEEE 802.11ad PBSS was followed by the IEEE 802.11ay task group to enhance the throughput and other functionalities [32], [33], [34], [35]. Although the IEEE 802.11ay task group added many scenarios outside the mmWave WPANs, e.g., AP deployment in outdoor spaces or indoor open spaces [67] and fixed access [35], IEEE 802.11ay also enhanced the PBSS designed by the previous IEEE 802.11ad task group as an enhanced DMG (EDMG) system. The major upgrade made by IEEE 802.11ay is a multichannel operation with up to four channels that uses multiple radio frequency (RF) chains to support MIMO. Accordingly, several additional functionalities related to A3 and A4 are discussed based on the IEEE 802.11ad operational structures, which are briefly introduced as follows.

Considering the procedures to initiate, discover, and join the network (A3), several functionalities are added to support multichannel operations and multiple RF chains. For instance, the PCP in IEEE 802.11ay should carefully decide on multiple operating channels, in contrast to the IEEE 802.11ad PCP, which selects only one operating channel. In addition, for transmitting beacons, the PCP in the IEEE 802.11ay PBSS is allowed to transmit beacon frames with multiple RF chains during a BTI [32] whereas the PCPs in IEEE 802.11ad are allowed only one RF chain. Finally, during the association, the PCP in IEEE 802.11ay can perform R-TXSS with multiple STAs simultaneously during the A-BFT by allocating multiple channels. This enhances the efficiency of beamforming between the PCP and the joining STAs.

For the multiple-access method (A4), scheduling flexibility is enhanced by multichannel operations. A PCP in an IEEE 802.11ay PBSS can allocate multiple SPs and CBAPs that occur in the same time period and in different channels, allowing simultaneous transmission among member STAs [32]. Moreover, a PCP in IEEE 802.11ay PBSS also allocates the CBAP and SP within multiple channels to allow transmission with channel bonding/aggregation [32]. Moreover, the SP can be further divided into a fine-grained fraction of time slots, which enhances the flexibility in scheduling STAs [32]. This mechanism is called a time-division duplex (TDD) SP and is intended to enhance the coexistence of multiple APs for the applications of a fixed access network [35].

However, the basic network structure and operation are the same as A1–A5 of the IEEE 802.11ad PBSS, because IEEE 802.11ay largely follows IEEE 802.11ad. Moreover, all the above enhancements are not specialized for mmWave WPANs; for instance, the TDD SP is applied in fixed-access use cases [35]. Hence, when limiting the discussion to a mmWave WPAN and its network formation procedure, A1–A5 in IEEE 802.11ad mostly answered Q1–Q3, which is sufficient for the objective of this survey. For detail protocols on IEEE 802.11ay, readers are encouraged to consult [32], [34].

E. Other MAC Functionalities Specific to IEEE 802.15.3c Piconet and IEEE 802.11ad PBSS

Finally, we show other newly defined MAC functionalities for mmWave WPAN in the IEEE 802.15.3c and IEEE 802.11ad task groups. These are exemplified by the frame aggregation and block acknowledgment (ACK) mechanisms (both IEEE 802.15.3c and IEEE 802.11ad), unequal error protection (IEEE 802.15.3c-only), beamforming protocols (IEEE 802.15.3 c and IEEE 802.11 ad), spatial sharing methods (IEEE 802.11ad-only), and relay methods (IEEE 802.11ad-only). These are briefly introduced in this section to shed light on the design sidelink-based mmWave WPANs detailed in the subsequent sections.

Frame Aggregation and Block ACK: Within the IEEE 802.15 standardizations, the IEEE 802.15.3c task group first discussed and defined a frame aggregation and block ACK mechanism to take advantage of high-speed mmWave communication [68], [69], [70], [71]. Therein, each unit of frames received from a MAC layer, termed the MAC service data unit (MSDU), is added by a frame check sequence (FCS) so that the receiver can find an MSDU-wise error. This yields one subframe. Multiple subframes are aggregated into a single frame, followed by the addition of header sequences. On the receiver side, the error of each subframe is checked and the receiver DEV acknowledges the identifier of the erroneous subframes to the transmitter DEV; this is known as the blockade of the ACK mechanism. Notably, in the

IEEE 802.11 standardization, this frame aggregation and block ACK mechanism was developed in the IEEE 802.11n task group that enhanced the 2.4/5 GHz WLAN [72]; hence, these mechanisms are not the first to the IEEE 802.11ad. Nonetheless, these mechanisms are useful for the development of mmWave WPAN systems.

Unequal Error Protection: Unequal error protection is a process in which transmitted bits are protected using different coding schemes depending on their significance. This scheme was first discussed in the IEEE 802.15.3c task group [71], [73] based on the concern that bit streams are biased in terms of significance in video streaming use cases [73]. For example, in IEEE 802.15.3c, the most and least significant bits can be protected using an LDPC code with different coding rates [22] in several MCSs.

Beamforming Protocol: Both the IEEE 802.15.3c and IEEE 802.11ad task groups defined a beamforming protocol, which was not found in previous systems operating in microwave bands. In addition to the alignment of quasi-omnidirectional beams described in Section II-A for A3, the IEEE 802.15.3c task group defined a beamforming protocol to align higher directional antennas between DEVs [47]. As in the beamforming of quasi-omnidirectional beams, the beamformer is codebook-based, and a similar protocol for quasi-omnidirectional beams was applied to align higher directional antennas. To reduce the search space of beam codebooks, which raises the issue of highly directional antennas, the IEEE 802.15.3c task group developed a hierarchical approach in which quasi-omnidirectional antennas are first aligned with an exhaustive beam search. Subsequently, highly directional antennas are aligned by an exhaustive beam search within a limited search space under the umbrella of quasi-omnidirectional antennas, reducing the complexity of the beamforming protocol. Notably, the beamforming protocol can be performed between a PNC and non-PNC DEV as well as between non-PNC DEVs; in this case, a beamforming protocol generally occurs during a CTAP.

The beamforming protocol in IEEE 802.11ad was proposed to be similar to IEEE 802.15.3c in the sense that IEEE 802.11ad also applies a codebook-based beamforming protocol [59], [74], [75], [76]. Moreover, the beamforming protocol in IEEE 802.11ad PBSS is not technically an exhaustive beam search because, as discussed in A3 for the I-TXSS and R-TXSS, one STA uses a directional antenna, whereas the other STA uses a quasi-omnidirectional antenna during beamforming, which reduces the computational complexity relative to an exhaustive search. In addition to TXSS, which trains only transmit directional antennas, the IEEE 802.11ad STAs can also train receiver directional antennas. This is referred to as the RXSS and is completed in a protocol similar to TXSS.

The IEEE 802.11ad task group further specified a beam refinement protocol (BRP) that follows the TXSS/RXSS in order to refine the beams found in the TXSS/RXSS in the case that these beams were suboptimal. Moreover, during BRPs, beamforming can be beyond codebook-based, implying that the STAs can optimize their continuous AWV without choosing a predefined AWV. During a BRP, predefined training sequences based on a Golay sequence are appended to the exchanged transaction frames; thereby, the STAs can optimize the antenna patterns. The details of the beamforming protocol are reported [27], [30].

Spatial Sharing Method: IEEE 802.11ad explicitly discusses spatial sharing [55], [77], [78] and defines specifications for the procedure [27]. This is motivated by the fact that the STA uses directional antennas and does not emit signals in every direction, resulting in less interference to the other STAs. Therefore, two or more pairs of STAs can communicate concurrently on the same channel.

Spatial sharing can be achieved by the PCP scheduling multiple SPs overwrapped in time during DTI, each of which is for a specific pair of STAs. To perform allocation, the PCP first requests a pair of beamformed STAs to measure the interference level from another pair of STAs. Based on the measurement results, the PCP decides to schedule the overwrapped SPs to mitigate the interference that occurs between the STAs communicating during the scheduled SPs. The IEEE 802.11ay task group discussed the extension of this method to multichannel operations [79] and defined a method for accessing the interference level across multiple channels [32].

Relay Operation: The IEEE 802.15.3c and 802.11ad task groups discussed relay operation [80], [81] to combat a line-of-sight blockage effect or other disruptions by switching propagating paths to circumvent the original propagating path. Based on the discussion, IEEE 802.11ad specified the following two relay-operation types [27]: 1) link-switching type and 2) link corporation type. In both the types, STAs allowed only single-hop relays, wherein a source STA can possess a direct link to a destination STA and single-hop relay link via a relay STA. The link-switching type operation activates only the direct link or relay link, whereas the link corporation type operation simultaneously activates both the links.

In the IEEE 802.11ad PBSS, for both relay operation types, a relay link was established with the help of a PCP. First, the source STA requests a list of candidates of the relay STAs to the PCP, and the PCP responds by passing the list. Subsequently, the source STA chooses one relay STA after surveying each joint channel status of the source STA-relay STA beamformed link, and relays the STA-destination STA beamformed link.[8] Finally, the source and destination STAs establish a link with the selected relay STA by exchanging the relay link setup frames. In IEEE 802.11ay, the relay operation is not updated [34], despite the problem statement present in the task group, indicating that the IEEE 802.11ad relay method lacks support for multihop operations [82].

III. REVIEW OF 3GPP SIDELINK ACCESS METHOD UNDER OUT-OF-COVERAGE OF BS

Given the aforementioned review of distributed mmWave WPANs, we analyze the current sidelink communication design and explore the difference between mmWave WPAN and sidelink communication in terms of the methodology to form a communication link among nodes. To this end, we first

[8]Hence, beamforming with the relay STA is necessary to perform channel measurements. For the beamforming protocol at this stage, only sector-level sweep is allowed, meaning that the BRP cannot be used [27].

review the current sidelink communication design focusing on the usage scenarios and communication modes defined therein. Moreover, we review the current standardization activities to support mmWave bands. Second, by focusing on sidelink unicast communications under out of coverage, we review the aforementioned five points of view (A1–A5) to focus on the protocol to establish the communication link. Finally, for points of view A1–A5, we provide a gap analysis between IEEE 802-based distributed autonomous mmWave WPANs and the current sidelink communication design under out-of-coverage scenarios.

A. Review of Sidelink Communication and Standardization Activities

Sidelink communication was defined to allow a UE to directly transmit frames to other proximity UEs with the air interface defined in the 3GPP. Sidelink communication was originally defined as a tool for device-to-device communication in Release 12 [15], [16] where the application focus was on public safety. Subsequently, the sidelink communication has evolved under the umbrella of V2X communications, where an advanced sidelink was developed under Release 14 [17], and a new 5G NR sidelink was standardized with a special focus on 5G NR V2X applications under Release 16 [10]. In this section, to provide a comprehensive view, we review the sidelink communication scenarios, sidelink communication modes, and current activities to support a mmWave band. Subsequently, we summarize the review in view of the extension of sidelink communication for the mmWave WPAN.

Sidelink Communication Scenarios: Sidelink communication scenarios are briefly categorized into in-coverage and out-of-coverage scenarios. In in-coverage scenarios, a transmitting UE is connected with a cellular BS, where resource allocation and timing synchronization are both conducted with the help of the BS. Therein, the resource is allocated by the BS in response to the request from UEs where the selected resources for sidelink communication are informed via the downlink control indicator in the Uu link. This resource allocation method is termed Mode 3 in the LTE sidelink and Mode 1 in 5G NR sidelink. As detailed later, the 5G NR sidelink supports HARQ; hence, the UE supporting the 5G NR sidelink can request resources for HARQ retransmissions.

Meanwhile, in out-of-coverage scenarios, a transmitting UE is not covered by any cellular BSs, and the resource allocation and timing synchronization are performed in a fully decentralized manner. Therein, the resource is allocated by the transmitting UE such that collisions among other UEs are avoided based on sensing of past frame transmissions of the UEs. This resource allocation mechanism is termed Mode 4 in the LTE sidelink and Mode 2 in the 5G NR sidelink. Moreover, for timing synchronization with potential receiver UEs, a UE should transmit a synchronization frame with PSBCH. This operation scenario is fully covered in Section III-B.

Sidelink Communication Modes: Up to now, the 3GPP has defined the following three sidelink communication modes: 1) broadcast; 2) groupcast; and 3) unicast communications. In the era of the LTE V2X sidelink, only broadcast communication was defined [17] to allow vehicles to notify basic awareness messages, which was similar to the precedented dedicated short-range communication (DSRC). As the evolution for the 5G NR sidelink, the 3GPP additionally defined groupcast and unicast communication modes to meet more complicated information flow for upcoming advanced V2X applications (e.g., vehicle platooning and cooperative perception among vehicles). Moreover, for all communication modes, the HARQ operation was defined in the 5G NR to enhance the reliability of packet delivery, where the retransmission and ACK/non-ACK mechanism were newly defined.

In the sidelink broadcast communication, a transmitting UE is not aware of any receiver UEs, and in this sense, these UEs are not connected on the network layer. This communication mode is intended to disseminate several awareness messages and is not intended to conduct bi-directional communication among UEs. The LTE sidelink only supports periodic transmission, and the retransmission was not supported. In the 5G NR sidelink, this issue was solved, where blind retransmission is now supported, and the UEs can perform not only a periodic transmission but also aperiodic transmission.

In the sidelink groupcast communication newly defined in the 5G NR sidelink, a transmitting UE disseminates messages for a target group of UEs. This communication mode can be interpreted as an advanced version of broadcast communication in the sense that the groupcast communication can enhance reliability by limiting the receiver UEs as a group. Therein, the HARQ retransmission is defined where the group UEs can transmit an ACK or non-ACK via a physical sidelink feedback channel (PSFCH) to notify the success or failure of the message reception [10]. Moreover, based on the ACK/non-ACK, the transmitter UE can retransmit the same message, thereby enhancing the reliability of packet delivery. Note that as in broadcast communication, groupcast communication is not intended to conduct bi-directional communication among UEs, and the grouped UEs are hardly connected on the network layer.

Finally, in the sidelink unicast communication newly defined in the 5G NR sidelink, a transmitting UE can transmit a packet in a specific receiver UE. Here, a UE can establish a connection with another UE on the access layer and even the network layer. As opposed to the broadcast and groupcast communications, the sidelink unicast communication involves a more complicated protocol to initiate and maintain the unicast link as detailed in the next section, where a bi-directional communication can be performed between the UEs. Moreover, the HARQ mechanism is defined where the receiver UE can send ACK or non-ACK via PSFCH preconfigured between the UEs. Based on the ACK or non-ACK, the transmitter UE retransmits the same packet via a resource reserved for retransmission.

Activity for Supporting mmWave Band: The 5G NR sidelink mainly aims for an operation in the frequency range 1, i.e., 410 MHz–7.125 GHz, and there are no optimized specifications for mmWave bands at the time of writing. In the last release from the 3GPP, a work item was established for the usage of the mmWave band; however, the work item exhibited a limited scope, that is, specifying only an

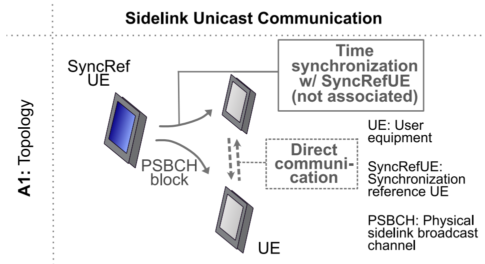

Fig. 13. A1: Topology in sidelink unicast communication under out of coverage of BSs.

evaluation methodology and beam management mechanism in the licensed spectrum [83]. As the evaluation methodology, a deployment scenario was discussed to be a simple indoor office and urban street canyon, and several parameters for simulations were also discussed [84]; however, this is not a technical specification. For the beam management mechanism, the 3GPP did not reach any agreements for concrete technical specifications in the sense that candidate protocols were not down-selected [84]. Hence, the 5G NR sidelink is yet to be optimized for the mmWave bands, and defining the 5G NR sidelink for mmWave bands is now open discussion.

Summary: To summarize, the current 5G NR sidelink communication is a simplified communication mechanism in the sense of the following two points: 1) the 5G NR sidelink only supports information dissemination (i.e., broadcast and groupcast) and point-to-point communication (i.e., unicast), not forming a network and 2) the 5G NR sidelink is yet to be optimized for the mmWave band. This simplification is reasonable to quickly meet the demand for V2X applications. However, as detailed in Section I, departing from this simplification is worth considering to accommodate more complicated information flow at a high rate, which will underpin the futuristic autonomous distributed systems operated more intelligently. Thus, in the next section, we revisit the sidelink unicast communication, which is the only communication mode to allow bi-directional connectivity between UEs, and discuss the possibility of forming a mmWave WPAN based on the sidelink unicast communication. Note that we consider that all UEs are out of coverage of a BS because our targeted system design is sidelink-based mmWave WPANs that can autonomously form a network under out-of-coverage scenarios.

B. Sidelink Unicast Communication Under Out-of-Coverage From Viewpoint A1–A5

A1 (Topology): Technically, there are no notions of "network topology" in sidelink unicast communication under out-of-coverage because the current sidelink communication is not intended to form a wireless network, but to form a point-to-point link between UEs. Nonetheless, the nodes communicating via sidelink unicast communication exhibit a unique structure, as shown in Fig. 13. First, one adjacent UE or the UE involved in sidelink communication, termed the synchronization reference UE (SyncRefUE), serves as a synchronization source that helps adjacent nodes synchronize with each other in terms of orthogonal frequency division multiple access (OFDMA) slot timing and a slot index. This synchronization is achieved by SyncRefUE broadcasting a synchronization frame termed the PSBCH block [85], which occupies one OFDMA slot[9] and contains both a timing synchronization sequence based on the M-sequence/Gold-sequence [86] and information on a current slot index [87], [88]. The M-sequence was chosen because of its better autocorrelation property [86] compared with the Zadoff–Chu sequence used in the preceding LTE sidelink synchronization signal [89] under frequency offsets that occur in a higher frequency band. Based on slot synchronization, the UEs can start a sidelink unicast communication. Notably, more than two UEs can be involved in a UE-to-UE (U2U) relay, wherein two UEs can communicate with each other via another relay UE. The U2U relay procedure is under discussion for Release 18 in terms of relay selection metrics, identifier, relay reselection method, signaling protocol at a higher layer [90], [91], [92], etc., and a concrete protocol has not been decided at the time of writing.

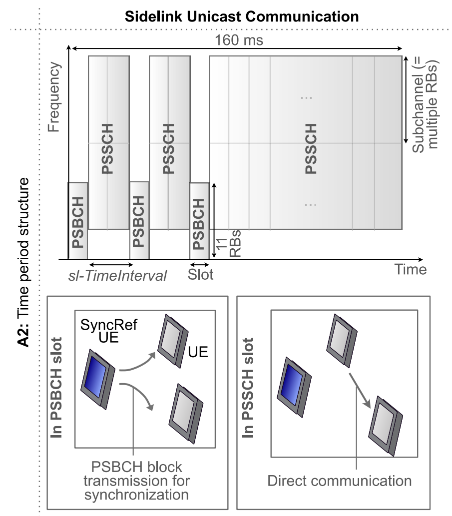

Fig. 14. A2: Time period structure in sidelink unicast communication.

A2 (Structure of Time Periods): Technically, in the sidelink communication, there are no notions of superframe as in the IEEE 802.15.3c and IEEE 802.11ad. However, a repeated period of time slots that starts with the transmission/reception of a broadcast signal, that is, a PSBCH block that occupies 132 orthogonal frequency division multiplexing (OFDM) symbols, exists, and we introduce such a time period, as shown in Fig. 14. The period length was set to 16 frames,[10] resulting in 160 ms [93]. During this period, up to 64 PSBCH blocks can be transmitted, which is predetermined by the UE. The number of transmitted PSBCH blocks is called *sl-NumSSB-WithinPeriod* [87]. If a SyncRefUE transmits multiple PSBCH blocks, the interval of the adjacent PSBCH blocks is identical, which is also predefined by SyncRefUE with the parameter name *sl-TimeInterval* [87]. The other slots are termed physical sidelink shared channel (PSSCH) blocks, where user data, control information, and other acknowledgment signals are exchanged between the UEs.

[9]In the 3GPP 5G NR, "slot" is referred to as 14 OFDM symbols for a normal length of cyclic prefix [85]. For extended cyclic prefixes, a slot is referred to as 12 OFDM symbols [85].

[10]In the 3GPP 5G NR specification, "frame" is referred to as 10 ms [85]. Hence, 16 frames correspond to 160 ms.

Notably, because the sidelink communication is operated based on OFDMA, the PSSCH resources can also be subdivided in the frequency domain. A minimum unit for the frequency resource is termed a "subchannel," which is referred to as a bundle of multiple resource blocks (RBs).[11] The number of RBs that one subchannel contains is implementation-specific and predetermined in the parameter set termed *SL-ResourcePool* [87]. Therefore, the available PSSCH resources have a mesh shape, as shown in Fig. 14, over which the UEs compete with one another to perform data transmission. The methodology for acquiring the transmitting resources is described in A4 in this section. The slot for the PSBCH does not involve PSSCH resources, even if the PSBCH does not occupy all available frequency resources inside the slot [87].

A3 (Procedures to Initiate SyncRefUE, Discover Nodes, and Initiate Sidelink Unicast Communication): As the sidelink unicast communication is not intended to form an autonomous and distributed wireless network as in WPAN, this point-of-view cannot be summarized as "procedures to initiate, discover, and join network" as in Section II. However, the procedure for starting sidelink unicast communication involves similar steps. Therein, SyncRefUE starts with a PSBCH block, which is reminiscent of a PNC/PCP transmitting a beacon frame. Moreover, a specific discovery procedure is optionally performed to discover a communication node, and sidelink unicast communication is established by associating with the discovered node. The procedure is as follows:

To start the transmission of a PSBCH block, a UE, that is, a potential SyncRefUE, first searches for an existing synchronization source, thereby confirming the necessity of becoming a SyncRefUE, as shown in Fig. 15. If the out-of-coverage condition is considered, the following two types of synchronization sources exist: 1) a global navigation satellite system (GNSS) and 2) a PSBCH block transmitted by another SyncRefUE [87]. If the UE can synchronize with a GNSS with sufficient timing reliability [94], the UE immediately transmits a PSBCH block and becomes SyncRefUE so that another UE that does not reach any GNSSs can synchronize with the UE. When the UE cannot synchronize with any GNSSs with sufficient reliability, it searches for a PSBCH block to decide whether to become a SyncRefUE. If the UE cannot receive a PSBCH block with a reference signal received power (RSRP) threshold named *syncTxThreshOoC* in a preconfiguration, the UE becomes SyncRefUE and transmits a PSBCH block with predefined slot timings. Notably, the other UEs in the proximity of SyncRefUE also follow the aforementioned scan procedure and confirm that the PSBCH block transmitted by SyncRefUE can be received with the RSRP above the *syncTxThreshOoC*. Subsequently, the UEs synchronizes with SyncRefUE by receiving the PSBCH block.

Subsequently, the synchronized UEs can discover a target UE to start the sidelink unicast communication. This is achieved using a framework called proximity service (ProSe) direct discovery over the PC5 interface [95], [96], [97]. The

[11]In the 3GPP 5G NR specification, "RB" is referred to as 12 OFDM subcarrier [85].

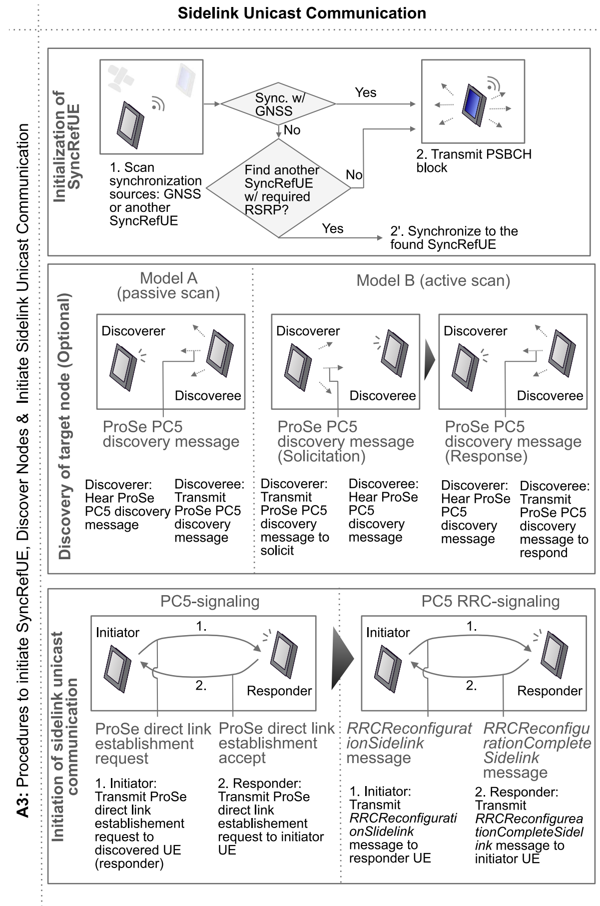

Fig. 15. A3: Procedures to initiate SyncRefUE, discover nodes, and initiate sidelink unicast communication.

discovery procedure is categorized into the following two types depending on whether the message exchange is unidirectional or bidirectional, as shown in Fig. 15, which is similar to passive scanning and active scanning in IEEE 802.11ad. In the first framework, termed Model A discovery, a UE that works as a discoveree periodically transmits over a PSSCH block an announcement message termed a ProSe PC5 discovery message [97] that includes the UE identifier. This message is transmitted in the broadcast mode and does not specify its destination. The other UEs monitor the discovery message and determine that the discoveree UE exists in proximity with its identifier. In the second framework, Model B, as opposed to Model A, a discoverer UE initiates the discovery procedure by sending a ProSe PC5 discovery message to solicit responses from the discoveree UEs. Subsequently, a discoveree UE responds to the solicitation by transmitting a ProSe PC5 discovery message, at which point the discoverer UE finds that a UE exists in proximity. This message exchange is performed over the PSSCH blocks. Notably, at the time of writing this article, these discovery procedures were not mandatory with the subsequent procedure for initiating sidelink unicast communication, implying that the UE can discover another UE by sending a communication request message (mentioned below) and waiting for its response.

Finally, a pair of UEs establishes a sidelink unicast link and initiates sidelink unicast communication. As the first step, a UE interested in initiating sidelink unicast communication transmits a ProSe direct link establishment request [97] to the target UE to be communicated with. If this step is initiated after the aforementioned discovery procedure, and the initiating UE intends to establish a link with the discovered UE, the initiating UE specifies the discovered UE as the destination of the ProSe direct link establishment request message. Otherwise, the initiating UE transmits the ProSe direct link establishment request message in a broadcast mode without specifying the destination UE. Subsequently, a UE that receives the request responds by transmitting a ProSe direct link establishment accept message to accept the request to the initiating UE.[12]

At this point, the UE pair may be able to perform sidelink unicast communication from the viewpoint of the application layer; however, additional information exchange to manage the link from the viewpoint of radio resources is necessary. Hence, a pair of UEs can invoke a PC5-radio resource control (RRC) signaling, where information related to radio management is exchanged [87], [98]. First, each UE transmits a message termed *RRCReconfigurationSidelink* [87] to the paired UE to inform the configuration of the link measurement and other reference signal configurations. Moreover, an *RRCReconfigurationSidelink* message also includes other lower layer configurations[13] so that the pair of UE can set up a logical channel through which sidelink unicast communication is performed. After receiving the message, the paired UE responds by transmitting a message termed *RRCReconfigurationCompleteSidelink* [87], thereby completing PC5-RRC signaling.

A4 (Multiple Access Method): Sidelink communication operated under out of coverage of BSs applies a distributed resource allocation method termed "Mode 2" resource allocation [20]. In Mode 2 resource allocation, the UEs compete for PSSCH resources and acquire a number of time and frequency resources (i.e., a slot and several subchannels) in a distributed manner, implying that the resources are not reserved by any central controller. In this sense, Mode 2 resource allocation is similar to contention-based multiple access. The Mode 2 resource allocation consists of the following two types: 1) dynamic scheduling and semi-persistent scheduling (SPS), which are applied to the transmission of one MAC protocol data unit (MPDU), or transport block (TB) and 2) multiple TBs [10], [20], respectively.

In dynamic scheduling, a transmitting UE selects a set of multiple PSSCH resources for the initial transmission of a buffered TB and the retransmission of the same TB as follows: first, as shown in Fig. 16, a UE regularly senses the channel and decodes a part of the signals transmitted by other proximal UEs over a PSSCH block. Specifically, the UE decodes the first-stage sidelink control information (SCI) [102], which includes information on resources reserved by the proximal UEs for the future. Based on the sensing result, the UE creates a list of available resources by excluding the resources reserved by the proximal UEs whose signals are above an RSRP threshold that is predetermined depending on the QoS requirement of the UE [103]. If the available resources are too scarce and the number of available resources does not meet a predefined requirement, the UE can increase the RSRP threshold by 3 dB to enable simultaneous usage of resources, thereby ensuring that a sufficient number of resources are made usable. Then, prior to the transmission of the TB, the UE checks the current list and randomly selects resources from it. In the selected resource, the UE performs an initial transmission of the TB along with the first-stage SCI, including the identifiers of one or two resources, used for subsequent retransmission [102]. This step allows notification of the selected resources for the upcoming retransmission, and the other proximal UEs cease transmission on the same resources. Moreover, during the retransmission of TB, the UE also transmits the first-stage SCI, including the identifier of the selected resources for the upcoming retransmission.

The same principle applies to the SPS, except that the UE also performs periodic transmission of multiple buffered TBs [20]. This period, termed the resource reservation period (RRP), is also notified to other UEs via the first-stage SCI, and the other UEs predict the future resource that they cannot

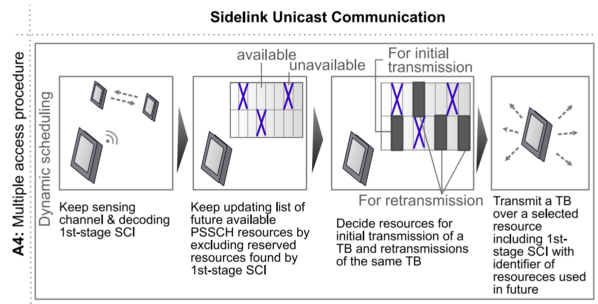

Fig. 16. A4: Multiple access method in the sidelink communication under out-of-coverage.

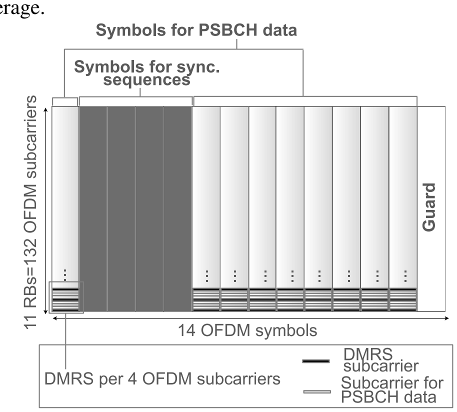

Fig. 17. Structure of a PSBCH block for a normal cyclic prefix length. For an extended cyclic prefix length, the PSBCH block occupies 12 OFDM symbols; two symbols for PSBCH data are removed from this figure.

[12]In between, the pair of UEs can invoke security information exchange to establish ciphering keys and integrity protection, etc. [96].

[13]Technically, "other lower layers" correspond to 1) service data protocol sublayer [99] that performs QoS flow management, 2) packet data convergence protocol sublayer [100] that performs sequence numbering, header compression/decompression, ciphering/deciphering, integrity protection, etc. 3) radio link control [101] sublayer that manages an acknowledged transmission, and 4) MAC layer [20] that performs multiplexing/demultiplexing MSDU, scheduling, error correction, priority handling, etc.

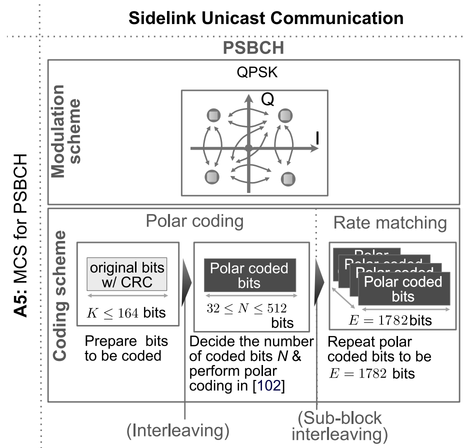

Fig. 18. A5: MCS for PSBCH for normal cyclic prefix length. For the extended cyclic prefix length, E should be modified to 1386.

use to transmit their TBs. Thus, the resources for most TBs can be reserved in the SPS.

A5 (MCS for PSBCH): As sidelink communication is not intended to form a wireless network, there is no concept of a beacon. However, the PSBCH block plays a role similar to that of a beacon frame in the sense that the PSBCH block helps synchronize the UEs with each other. Hence, we briefly introduce the specifications and MCS of the PSBCH block as follows:

The number of OFDM symbols and subcarriers occupied by a PSBCH block is strictly specified in [85]. The PSBCH block occupies only one slot, that is, 14 OFDM symbols, and 11 RBs, that is, 132 subcarriers per symbol, as shown in Fig. 17, in the normal cyclic prefix length. The PSBCH block occupies 12 OFDM symbols for an extended CP length. Inside the block, the second, third, fourth, fifth, and fourteenth symbols are not used for data transmission, where the former four symbols are occupied by timing synchronization sequences, and the last symbol works as a guard period. Moreover, inside each residual slot, a pilot subcarrier termed the demodulation reference signal (DMRS) is included for every four subcarriers, and the modulated symbols are mapped to the residual 891 subcarriers for the normal cyclic prefix length and 693 for the extended cyclic prefix length.

As shown in Fig. 18, the modulation scheme is quadrature shift keying (QPSK), which leads to the number of coded bits being 1782 bits for the normal cyclic prefix length and 1386 bits for the extended cyclic prefix length. Hence, coding is performed to satisfy this number. Let $E \in \{1782, 1386\}$ and K be the number of transmitted bits, including cyclic redundancy check (CRC), added to the original bits. Notably, in the 3GPP specification, K is enforced to be less than or equal to 164 bits for the PSBCH block because of the maximum number of bits for interleaving performed before the coding [102].

The channel coding is performed using these parameters. First, the UE determines the number of coded bits $N = 2^n$, where $n = \max\{\min\{\lceil 8K \rceil, 9\}, 5\}$ [102], [104]; hence, n ranges from 5 to 9 and N ranges from 32 to 512. Subsequently, polar coding, which is one of the capacity-achieving codes [105], is applied with a code rate of K/N, resulting in N coded bits. Therein, $N-K$ zero bits are inserted into the K original bits and $N \times N$ predefined generation matrix is applied. For PSBCH, this operation is performed without using the parity-check sequences that are sometimes used for other data types [102]. Subsequently, the rate matching is applied, where because $E < N$ for any case, the N coded bits are repeated to let the resultant number of bits be E [102]. In summary, the overall code rate in PSBCH is K/E, and except for the repetition in the rate matching, the polar code is applied as the main coding scheme in PSBCH. Notably, bit interleave is performed before and after polar coding, whereas the latter interleave is performed to divide the blocks of the coded bits [102], [104].

C. Review Summary and Comparison Analysis From IEEE 802-Based mmWave WPAN

As discussed before, the current sidelink communication under out-of-coverage scenarios is different from the IEEE 802-based mmWave WPAN systems. This section compares these two systems based on A1–A5 to identify the missing research building blocks that are essential for realizing sidelink-based mmWave WPANs discussed in Section I-B.

First, with respect to topology (A1), the IEEE 802-based mmWave WPAN applied a star topology, in which direct communication between nodes was allowed with the help of a network coordinator, that is, a PNC or PCP. Meanwhile, the current sidelink unicast communication is not intended to build a mmWave WPAN; hence, only point-to-point communication is allowed. Nonetheless, to initiate sidelink unicast communication under out-of-coverage scenarios, SyncRefUE is required for OFDMA slot synchronization among proximal UEs. This suggests that if SyncRefUE not only works as a synchronization source but also as a network coordinator, an IEEE 802-based mmWave WPAN can be created based on the sidelink unicast communication framework. This is discussed in detail in Section IV.

The superframe structure (A2) of the current sidelink communication networks is simpler than that of the IEEE 802-based mmWave WPANs, because the current sidelink communication devices operate in the low-frequency band supported by omnidirectional antennas. In this case, the time-period fractions specialized for beamforming are not necessary, unlike the superframe in the IEEE 802-based mmWave WPAN. This time-period structure should also be considered for sidelink communications to support mmWave communications.

The network initialization procedure (A3) for both the communication systems exhibits similarities, i.e., both start with a channel scan, transmit broadcast signals for synchronization, discover nodes, and are associated with a node. However, as explained in A1, in the discovery procedure of sidelink communication, a node discovers arbitrary nodes, whereas in the IEEE 802-based mmWave WPAN, the nodes first discover a network coordinator and immediately associate with it. This technique is worth revisiting to simplify the procedure for forming a WPAN based on sidelink communication, as elucidated in the next section. Moreover, to transmit a broadcast signal, that is, PSBCH, sidelink communication does not support transmission with directional antennas or association with directional antennas, which should be solved to support mmWave communication systems, along with the modification of the superframe structure.

For multiple access procedure A4, the sidelink communication under out-of-coverage scenarios does not use a network coordinator and applies Mode 2 resource allocation, which is similar to the contention-based access method. Meanwhile, IEEE 802-based WPAN systems apply a hybrid system of a contention-based access method and TDMA coordinated by a network coordinator. Recall that the IEEE 802.11ad task group intensively proposed the use of TDMA to support directional communication and avoided deafness problems (see Section II-B), the sidelink multiple-access method using only Mode 2 resource allocation should be reconsidered. This point is discussed in Section IV.

Finally, for the MCS for broadcast signal A5, both communication systems designed an MCS robustly such that the frame error was avoided against several wireless channel perturbations. In sidelink communications, PSBCH applies QPSK modulation, which exhibits the lowest modulation order among the modulation schemes for sidelink communications. This implies that the PSBCH should not target a higher rate; rather, it should achieve robustness. Moreover, polar coding is applied instead of the most commonly used LDPC because the former performs better, particularly when applied to a small payload (e.g., 250 bits or less [106]). Hence, the PSBCH design is similar to the IEEE 802.15.3c CMS and the IEEE 802.11ad control PHY in terms of robustness against channel perturbations. However, the current PSBCH limits the payload size to 164 bits because the PSBCH was designed to carry only information bits for slot synchronization [87], [88]. This number of carried bits is insufficient for carrying network management information, as in IEEE 802.15.3c CMS and IEEE 802.11ad control PHY,[14] which should be revisited, as discussed in the next section.

IV. PROPOSED RESEARCH BUILDING BLOCKS FOR SIDELINK-BASED MMWAVE PERSONAL AREA NETWORK

Based on the above discussion, we propose the research building blocks to achieve the 3GPP sidelink-based mmWave WPAN envisioned in Section I-B, focusing on MAC protocol perspectives, which leads to successful communication inside a WPAN. Our core idea is that IEEE 802-based mmWave WPAN designs should be revisited, and several essential system designs should be integrated into sidelink unicast communications. First, we propose the research building blocks from the viewpoints of A1–A5 and subsequently propose those from the other MAC-related components.

[14]The IEEE 802.15.3c CMS and IEEE 802.11ad control PHY can carry arbitrary numbers of bits technically; however, the typical number of bits for simulation seems to be approximately 200–300 Bytes [107], [108], which is much larger than the number of bits that the PSBCH carries. This value is also used for the simulation in this study.

A. Proposed Building Blocks for mmWave WPAN Formation Point-of-Views A1-A5

A1 (SyncRefUE as a WPAN Network Coordinator): As for the topology, the current sidelink unicast communication supports only point-to-point communication and is not explicitly specialized for building a WPAN. This system design should be revised, considering that the establishment of the IEEE 802-based mmWave WPAN and its successful operation are largely based on a network coordinator. A feasible step in realizing a sidelink-based mmWave WPAN is to define a network controller that plays the role of network synchronization as well as network management in terms of multiple accesses for sidelink communication. SyncRefUEs is a natural choice for such a network coordinator because SyncRefUEs already transmit beacon-like broadcast signals, that is, PSBCH, and perform synchronization among the proximal UEs. The residual challenges include adding other functionalities related to network management to SyncRefUEs. All the research blocks discussed below are intended to achieve this objective.

A2 and A3 (Defining Superframe Structure and Directional Access Method to SyncRefUE): When SyncRefUEs are defined as playing the role of network coordinators, the superframe structure and methodology for a UEs to associate with a SyncRefUE should also be defined. As a specific characteristic of mmWave communication, supporting a directional antenna for broadcast signal transmission and association is required, as in the IEEE 802-based mmWave WPAN designs. Based on the study of the IEEE 802-based mmWave WPAN superframe structure presented in Section II-A, the time-period structure for sidelink communication discussed in Section III-B should be designed such that the earlier part of the time period is specialized for the directional transmission of broadcast signals (i.e., PSBCH). Moreover, the directional transmission of the PSBCH is followed by a specialized time period to associate the UEs with a SyncRefUE while leveraging directional antennas for both sides. As an exemplary design, the time period starts by transmitting multiple PSBCH blocks while using different directional antenna patterns to cover all directions, which is followed by an association period where beamforming between the SyncRefUE and other associated UEs is performed.

A4 (Defining 5G NR-Compatible Multiple Access Method, Including Centralized Coordination): Sidelink unicast communication under out-of-coverage only applies a multiple access method similar to the contention-based access method based on OFDMA, whereas the IEEE 802-based mmWave WPAN applies a hybrid contention-based method and coordinated TDMA. Recalling that the coordinated TDMA is defined to fully support directional antennas while avoiding deafness problems in the IEEE 802.11ad task group, this coordinated TDMA should be considered for sidelink-based mmWave WPAN. This selection is further supported by the centralized-cellular-network origin of the 5G NR air interface, which may allow coordination of time resources for a SyncRefUE. However, identifying the mechanism underlying the optimization of the coordination by a SyncRefUE, which is in charge of the network controller, for transmission of member UEs with OFDMA systems is challenging. This mechanism is in stark contrast to those followed by IEEE 802.15.3c and IEEE 802.11ad, which use only one channel. Therefore, further investigations are required to address this challenge in detail.

A5 (Defining PSBCH Transmission Scheme as Beacon): As discussed in Section III-C, the current PSBCH block is highly insufficient to work as an IEEE 802-like beacon frame in terms of the number of carried bits. Recalling that the beacon frames of IEEE 802.15.3c and IEEE 802.11ad carry the necessary information for network management and should be capable of carrying several hundred bytes, extending the PSBCH transmission scheme to a beacon frame is essential. One research direction is to extend the PSBCH transmission to carry more bits, reaching at least several hundreds of bytes. Moreover, the MCSs for the transmission of the extended PSBCH as a beacon were designed to be as robust as the IEEE 802.15.3 CMS and IEEE 802.11ad control PHY. Given this design, a PHY link-level simulation should be performed. This type of PHY performance evaluation has yet to be performed because the current focus of PHY evaluation is on UE-BS communications [110], [111], [112], [113], [114], [115].

B. Proposed Building Blocks for Other MAC-Related Components

Finally, we discuss other research building blocks to realize and enhance the 3GPP sidelink-based mmWave WPANs outside points of view A1–A5 in correspondence with the items of the IEEE 802-based WPANs explained in Section II-E.

Defining Beamforming Protocol: This item should be prioritized for successful communication among nodes with mmWaves, because of the necessity of compensating for the large path loss in mmWaves. Nonetheless, because the 3GPP sidelink mmWave WPAN may first target communication in close proximity (e.g., several meters), highly directional antennas are not required, implying that the beam-search space can be smaller. Hence, for the beamforming technique, applying a codebook-based beamforming protocol, such as IEEE 802.15.3c and IEEE 802.11ad, may be a feasible choice. The remaining question is how to design such a beamforming protocol to be compatible with the OFDMA resource structure, which should be solved in the upcoming 3GPP standardization.

Another beamforming approach may be exemplified by leveraging situational awareness captured using sensory information, such as camera images [109], [116], [117], [118], [119] and positional information [120], [121]. Compared to the era of IEEE 802.15.3c and IEEE 802.11ad standardization activities, the computational resources of communication nodes have drastically increased, indicating that dealing with such high-dimensional sensory information using a computation-intensive method (e.g., machine-learning techniques) may be feasible. Current studies on sensory-information-based beamforming have concentrated on BS-STA communication, even though addressing shorter range communication for mmWave WPANs is much more tractable. Feasibility studies of such sensory-information-based beamforming methods and comparisons with codebook-based methods in view of WPAN scenarios are interesting research directions.

Defining Single/Multihop Relay Operation: Relay operation based on single- or multihop communication not only enhances coverage but also enhances robustness against channel perturbations owing to line-of-sight blockage events. This operation may be crucial for extending the 3GPP sidelink mmWave WPAN to large-scale, resilient mmWave networks. Currently, both IEEE 802.11ad/11ay and sidelink relays only define a single-hop relay, and a protocol for multihop operation has not yet been discussed. In the sidelink, the concept of a multihop sidelink [127] or that for optimizing the link [128] was recently proposed; however, the detail protocol is now under discussion. Hence, defining a protocol for relay operation should be addressed.

One challenge is to solve the tradeoff between the optimality and simplicity of the protocol. As discussed in Section II-E, the relay operation of IEEE 802.11ad requires the PCP to survey the signal quality for all the links involved (i.e., source STA-relay STA link and relay STA-destination-STA link) for all candidate relay STAs. This allows for the optimization of the end-to-end link quality. However, this exhaustive survey of the signal quality causes a large signaling overhead and may not be feasible for a multihop operation. The current sidelink relay applies a simplified protocol in which the nodes only check whether the signal quality exceeds a predefined threshold, which prohibits the search for the optimal link. Assessing this tradeoff is required.

Defining Protocol for Spatial Sharing: As explained in Section II-E, spatial sharing also enhances the spectral efficiency by allowing simultaneous transmissions for multiple pairs of nodes. Thus, examining the spatial sharing features is also crucial for realizing dense deployment of 5G NR nodes with sidelink-based mmWave WPANs. One research direction is to consider the extension of the IEEE 802.11ad spatial sharing method to be applicable to OFDMA systems, in which the degree of freedom for the frequency domain is added. Therefore, simultaneous co-channel transmission or frequency-division transmission should be selected using a network controller. Optimizing the selection and definition of a protocol is an interesting topic for future research.

V. Case Study—Proposal of PSBCH Block Format and Transmission Scheme as Beacon Frame

Finally, to illustrate the feasibility of the aforementioned vision, we present a case study of one of the aforementioned research building blocks. Among the research building blocks, we address "A5: Defining PSBCH Transmission Scheme as Beacon" in Section IV-A standing on the assumption that "A1: SyncRefUE as a WPAN Network Coordinator." This is a critical and urgent issue in realizing sidelink-based mmWave WPANs. First, we define the problem in detail. Next, the simulation scenarios and their parameters are described. Finally, the results of the performance evaluation are presented.

A. Problem Definition

As discussed in Section III-B, the current PSBCH block carries only 164 bits, including a CRC sequence, which does not

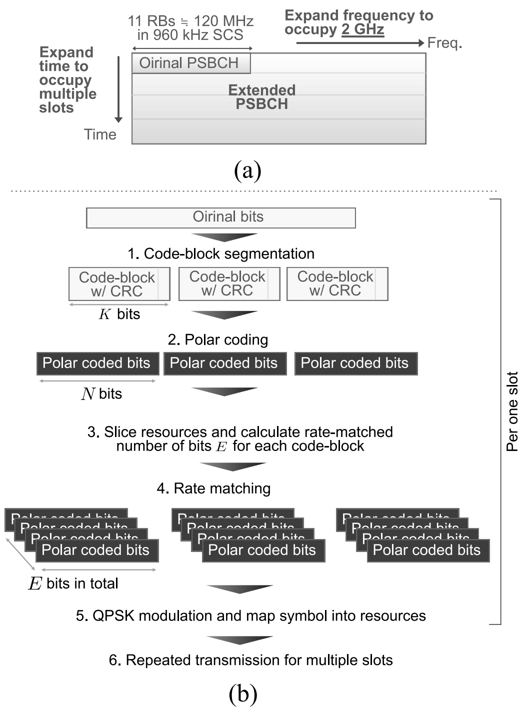

Fig. 19. Proposed extended PSBCH and transmission scheme. (a) Proposed extension of the PSBCH resources. (b) Proposed transmission scheme of the PSBCH block.

operate as a beacon frame to manage a WPAN. Thus, expansion of the resources used by the PSBCH block is necessary. However, the following question arises: How to define the PSBCH block format and transmission scheme so that the defined PSBCH block exhibits a performance comparable to that of the IEEE 802.15.3c CMS and IEEE 802.11ad control PHY? Hence, the objective of this section is to define both the PSBCH format and the transmission scheme to meet the following joint requirements: 1) the capability of carrying at least 200–300 bytes, including a CRC sequence as a payload packet and 2) comparable performance to the IEEE 802.15.3c CMS and IEEE 802.11ad control PHY in terms of PER.

B. Proposed Extended PSBCH Block and Transmission Scheme

Fig. 19(a) shows the proposed PSBCH block for achieving the above two joint objectives. First, we increased the occupied frequency resources to satisfy the first requirement of the number of bits carried as payload packets. The use of more frequency resources can be justified because the use of mmWaves ensures abundant frequency resources. As an example, we consider the usage of a bandwidth of approximately 2 GHz, which corresponds to the channel bandwidth of IEEE 802.15.3c and IEEE 802.11ad.

Moreover, we propose extending the PSBCH block not only for frequency but also for time resources. The motivation for this design was to meet the second requirement of comparable performance with the IEEE 802.15.3c CMS and IEEE 802.11ad control PHY. The IEEE 802-based standards, as discussed in Sections II-A and II-B, spreading was performed to enhance the robustness against a large path loss in mmWaves, implying that expanding the frame for time resources and defining a robust transmission scheme are necessary. This robust design must be revisited; otherwise, the PSBCH block will not satisfy the second requirement. Hence, as an extended PSBCH block design, we consider that the block occupies more than one slot for repeated transmission, and in conjunction with the transmission scheme discussed below, the robustness against large path losses can be drastically improved.

As a transmission scheme over the extended time-frequency resources, we employ a transmission scheme similar to that of the original PSBCH block, except that we leverage code-block segmentation to fit the requirement of polar coding in terms of the number of bits, and we leverage abundant resources for repeated transmission, as shown in Fig. 19(b). First, code-block segmentation is performed on the payload packets, thereby yielding segments that possess a number of bits comparable to the original PSBCH block, that is, fewer than 500 bits [102]. Subsequently, for each code block, we apply the same coding scheme as the original PSBCH block and obtain the polar-coded bits. Subsequently, we also allocate the available resources per slot into the same number as that of the code-block segments. For each code block segment and resource segment, rate matching is performed in the same manner as in A5 in Section III-B. Finally, repeated transmissions of the resultant slot are performed for multiple slots. Notably, as we consider the usage of abundant time-frequency resources, this procedure automatically ensures an increased number of repeated transmissions, and this increase in the number of repetitions in turn enhance the robustness of the transmitted bits.

C. Simulation Results

We compared the PER performance among the IEEE 802.15.3c CMS, IEEE 802.11ad control PHY, original PSBCH, and the proposed PSBCH. Table I shows the simulation parameters for each transmission scheme. As an initial study, we considered the additive white Gaussian noise (AWGN) channel, which is necessary to demonstrate that the proposed PSBCH block and its transmission scheme are comparable to the IEEE 802.15.3c CMS and IEEE 802.11ad control PHY. Moreover, we consider perfect synchronization to focus only on the ideal PER performance without synchronization performance.

Fig. 20 shows the PER performance of the IEEE 802.15.3c CMS, IEEE 802.11ad control PHY, original PSBCH, and proposed PSBCH. Notably, for the PSBCH, we term the PER as the block error rate (BLER), because the terminology is general for the 3GPP 5G NR; however, PER/BLER are used interchangeably. First, from the comparison between IEEE 802.15.3c and the original PSBCH, we find that the original PSBCH lacks both the number of carried payload bits and PER performance robustness against a low SNR. Technically, the IEEE 802.15.3c CMS was examined by setting the payload size to 239 bytes, whereas the original PSBCH was examined using a payload size of 164 bits. Nonetheless, by observing the SNR required to achieve a PER of 10^{-1}, the IEEE 802.15.3c

TABLE I
SIMULATION PARAMETERS

Parameter	Value
- Common Setup	
Channel	AWGN channel
Synchronization	Perfect
- IEEE 802.15.3c CMS and IEEE 802.11ad Control PHY	
Waveform	Single carrier
Payload size	239 Bytes
Chip rate/Sample rate in receiver	1.76 GHz
Modulation scheme	$\pi/2$-shift BPSK (15.3c), $\pi/2$-shift differential BPSK (11ad)
Roll-off factor of root-raised Nyquist filter	0.25
Coding scheme	Reed-Solomon (15.3c), LDPC (11ad)
Decoding scheme	Algorithm in [122] implemented in Matlab communication toolbox [123] (15.3c), Sum-product algorithm w/ simple LLR[1] definition in [124] for AWGN channel (11ad)
Spreading code	Golay code (15.3c [22], 11ad [27])
Spreading factor	64 (15.3c), 32 (11ad)
- PSBCH block	
Waveform	Cyclic prefix-OFDM
Cyclic prefix length	Normal
Payload size	164 bits (Original), 239 Bytes (Proposed)
Subcarrier spacing	960 kHz
Number of RBs	11 (Original), 157 (Proposed)
Bandwidth	126.72 MHz (Original), 1808 MHz (Proposed)
DMRS overhead	1/4
IFFT/FFT size	2048
Number of slots	1 (Original), 4 (Proposed)
Modulation scheme	QPSK
Number of code-block segments	*Nan* (Original), 10 (Proposed)
Coding scheme	Polar
Number of coded bits N for each code block	512
Decoding algorithm	Successive interference cancellation [125] with list size of 8
Number of rate-matched bits E	1782 bits (Original), 2543 or 2544 bits (Proposed)

1. LLR: Log-likelihood ratio. While calculating the LLR, clipping method [126] is applied, where the absolute value of the LLR is clipped to 10. For repeated transmission in the proposal, the LLR is added for the repeated bits.

CMS required a significantly a smaller SNR than the original PSBCH did. This result indicates that the original PSBCH block cannot operate as a beacon frame of IEEE 802.15.3c and IEEE 802.11ad, which falls short when overcoming "A5: Defining PSBCH Transmission Scheme as Beacon" in Section IV-A.

By comparing the IEEE 802.15.3c CMS with the proposed PSBCH extension and transmission scheme, the aforementioned issues can be overcome. This is because the proposed PSBCH was examined when setting the same payload size as the IEEE 802.15.3c CMS, and the PER performance approached that of the IEEE 802.15.3c CMS. This performance enhancement can be attributed to the diversity gain from repeated transmissions owing to both rate matching and multiple slots. In the simulation setting, the proposed PSBCH leveraged 157 RBs in the frequency domain, resulting in 2544 rate-matched bits E for each code block.

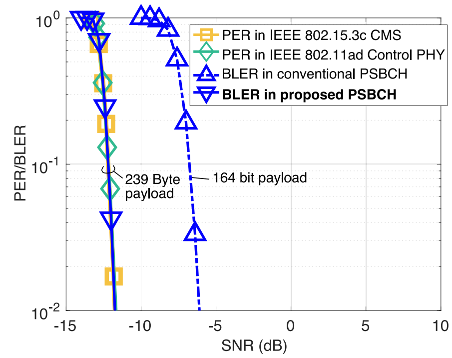

Fig. 20. PER/BLER performance of the IEEE 802.15.3c CMS, IEEE 802.11ad control PHY, original PSBCH, and proposed PSBCH.

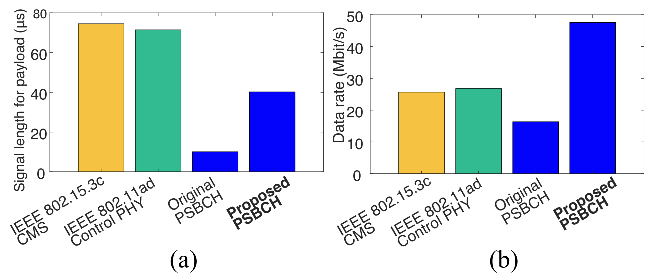

Fig. 21. Signal length occupied by the payload control data and data rate for the control data transmission. (a) Signal length occupied by payload. (b) Data rate achieved for payload transmission.

Recalling that the number of coded bits in each code block N was 512, the number of repetitions was approximately five, which is much higher than that in the original PSBCH block, that is, approximately three, in this simulation setting. Moreover, this slot is repeated for 4 slots, resulting in the original bits being transmitted approximately 20 times. Hence, a larger number of repetitions led to a better PER performance.

Fig. 21(a) shows the signal length occupied only by the payload for this simulation setting. The signal lengths of the IEEE 802.15.3c CMS and IEEE 802.11ad control PHY were calculated from the payload size, code rate, chip rate, and spreading factor. The signal lengths of the PSBCH blocks were calculated using the OFDM symbol length occupied by the payload. From Fig. 21(a), we can observe that the proposed PSBCH in this simulation setting, i.e., 4 slots expansion, exhibits a smaller signal length than both IEEE 802.15.3c CMS and IEEE 802.11ad, which might be attributed to the joint effects of coding gains and signal format differences. Moreover, as shown in Fig. 21(b), the proposed PSBCH transmission scheme exhibits a higher data rate than the original PSBCH transmission scheme, showing the possibility that a mmWave WPAN can be formed faster by using the proposed PSBCH transmission scheme. From these results, the proposed PSBCH can potentially outperform the IEEE 802.15.3c CMS, IEEE 802.11ad PHY, and original PSBCH transmission scheme, which sheds light on the feasibility of developing the sidelink-based mmWave WPAN systems envisioned in this study.

Notably, this simulation is regarding control data transmission to form a mmWave WPAN and does not dictate

TABLE II
LIST OF ABBREVIATIONS

A-BFT	association-beamforming training
ACK	acknowledgement
AP	access point
ATI	announcement transmission interval
AWGN	additive white Gaussian noise
AWV	antenna weight vector
BHI	beacon header interval
BI	beacon interval
BLER	block error rate
BPSK	binary phase shift keying
BRP	beam refinement protocol
BS	base station
BSS	basic service set
BTI	beacon training interval
CAP	contention access period
CBAP	contention-based access period
CMS	common mode signaling
CRC	cyclic redundancy check
CSMA/CA	carrier sense multiple access with collision avoidance
CTA	channel time allocation
CTS	clear to send
CTAP	channel time allocation period
DCF	distributed coordination function
DEV	device
DMG	directional multi-gigabit
DMRS	demodulation reference signal
DSRC	dedicated short-range communication
DTI	data transmission interval
EDMG	enhanced directional multi-gigabit
FCS	frame check sequence
GNSS	global navigation satellite system
IBSS	independent basic service set
I-TXSS	initiator transmission sector sweep
LDPC	low density parity check
LTE	long-term evolution
LLR	log-likelihood ratio
MAC	medium access control
MCS	modulation and coding scheme
MIMO	multiple input multiple output
mmWave	millimeter wave
MPDU	MAC protocol data unit
MSDU	MAC service data unit
NR	new radio
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PBSS	personal basis service set
PCP	personal basic service set control point
PER	packet error rate
PHY layer	physical layer
PNC	piconet coordinator
PRC	pairnet coordinator
ProSe	proximity service
PSBCH	physical sidelink broadcast channel
PSFCH	physical sidelink feedback channel
PSSCH	physical sidelink shared channel
QoS	quality of service
QPSK	quadrature phase shift keying
RB	resource block
RF	radio frequency
RRC	radio resource control
RRP	resource reservation period
RTS	request-to-send
R-TXSS	responder transmitter sector sweep
RSRP	reference signal received power
RXSS	receiver sector sweep
SCAP	sub-contention access period
SCI	sidelink control information
SNR	signal-to-noise ratio
SP	service period
SPR	service period request
SPS	semi-persistent scheduling
SSW	sector sweep
STA	station
SyncRefUE	synchronization reference UE
TB	transport block
TDD	time division duplex
TDMA	time division multiple access
TXOP	transmission opportunity
TXSS	transmitter sector sweep
UAV	unmanned aerial vehicle
UE	user equipment
U2U relay	UE-to-UE relay
V2X	vehicle to everything
WLAN	wireless local area network
WPAN	wireless personal area network
3GPP	third-generation partnership project
5G	fifth-generation
6G	sixth-generation

a data rate of subsequent user data transmission. However, the scope of this study is to discuss a design concept of the protocol to form a mmWave WPAN based on sidelink, which is generally done by using control data transmission. This control data transmission is crucial because unless the control data is successfully received, the subsequent high-rate user data transmission cannot be initiated. Thus, further investigation of user data transmission performance is beyond the scope and is cast as our future work.

VI. CONCLUSION

This article summarizes two separate standardization technologies: 1) IEEE 802.15.3/11-based mmWave WPANs and 2) sidelink communication. Interestingly, although the design principles of the former are lagging behind those of the latter, we can integrate them by focusing on the "A1: SyncRefUE as a network coordinator" (described as a fundamental research building block in Section V) owing to the star topology of the existing IEEE mmWave WPANs. Based on this starting point, we provide concrete research building blocks to fill the gap between these two systems to achieve 3GPP sidelink-based mmWave WPANs that solely rely on 5G NR air interfaces. Moreover, the presented case study for the proposal of a PSBCH to form an mmWave WPAN sheds light on the aforementioned concepts and ideas.

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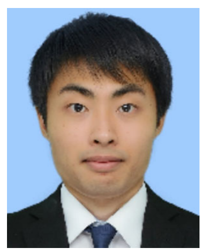

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