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Beam-Based Mobility Management in 5G Millimetre Wave V2X Communications: A Survey and Outlook

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ABSTRACT It is envisaged that 5G can enable many vehicular use cases that require high capacity, ultra-low latency and high reliability. To support this, 5G proposes the use of dense small cells technology as well as and highly directional mmWave systems deployment, among many other new advanced communication technologies, to boost the network capacity, reduce latency and provide high reliability. In such systems, enabling vehicular communication, where the nodes are highly mobile, requires robust mobility management techniques to minimise signalling cost and interruptions during frequent handovers. This presents a major challenge that communication system engineers need to address to realise the promise of 5G systems for V2X and similar applications. In this paper, we provide an overview of recent progresses in the development of handover and beam management techniques in 5G communication systems. We conduct a critical appraisal of current research on beam level and cell level mobility management in 5G mmWave networks considering the ultra-reliable and low-latency communication requirements within the context of V2X applications. We also provide an insight into the open challenges and the emerging trends as well as the possible evolution beyond the horizon of 5G.

INDEX TERMS Mobility, 5G mmWave, V2X.

I. INTRODUCTION

IT HAS been predicted that the world will encounter nearly 9 Billion mobile connections by 2025 and approximately 14% of them will be enabled by 5G [1]. While 5G New Radio (NR) - first version of 5G NR which is Phase 1 - the non-standalone (NSA) mode was completed with Rel. 15 along with some other enhancements to LTE in 2019, roll out has gain momentum rapidly and the total number of commercial 5G networks have reached 158 as of March 2021 [2]. The Rel. 16 (5G NR Phase 2) specifications are now finalised recently with some major extensions, new services and scenarios, as well as enhancements to the current 5G NR [3].

Due to explosive growth of data traffic, millimetre wave (mmWave) has become one of the promising candidate for 5G systems due to inadequacy of available spectrum and high data rate support in the current sub 6GHz microwave bands. With the higher bandwidth and low latency potentials of mmWave access for vehicular communication, it can fuel the development of autonomous driving by supporting high data demands and latency-sensitive applications [4]. However, mmWave channel is very susceptible to mobility and blockages, which will be more exacerbated in automotive environment [5]. Vehicle-to-everything, or V2X in short, is the key technology in 3GPP cellular networks to specifically deal with vehicular communications [6]–[8]. The 5G mmWave is a promising candidate for V2X, and the current development focus is to address the challenges of mmWave due to the high mobility vehicular scenarios [9].

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Despite the benefits of 5G mmWave access, transmissions at such high frequencies ($\gg$ 6GHz) often suffer from high propagation loss. To counter the high propagation loss, mmWave transmitters focus the transmission power towards at a specific direction to provide a practical transmission range. The directional transmission in mmWave, often called a mmWave beam, however introduces new challenges in communications, and the most prominent issue is the aspect of mobility management, especially for vehicular communication when the user equipment (UE) is a moving vehicle. For the connectivity, there is a need for accurate beam alignment and connection robustness against rapid channel changes [10], [11]. Moreover, new solutions for timely switching of beams are needed in the case of high mobility vehicles [12]. While being connected, the UE will encounter two types of mobility in mmWave, namely the cell level and beam level mobility as specified in 3GPP Rel. 16 [3] which are discussed in the following.

For cell level mobility, a UE experiences an inter base station handover. A 5G base station, or called gNB in a 3GPP specification, requires explicit Radio Resource Control (RRC) signalling to perform. Whereas for beam level mobility, the switching of beams occurs within the same gNB, and the control can be managed internally within the gNB. Unlike omnidirectional signal based access in LTE, directional signals are used in mmWave to utilise directivity gain for control operations as well, which ensure control signals to be received even at a long range where omnidirectional control signals may not be able to reach [13]. Note that directional beams are involved in both mobility type, thus accurate beam alignment between transmission and reception points becomes strictly necessary to establish a strong and reliable link. This may bring additional delay in connection time and significantly impacts control layer procedures, such as initial access, beam tracking and handover [13]. As the design of a mobility management solution depends on beam control and management technologies, this introduces challenges to the design of mobility management to not only utilise the current available beam control and management technologies, but also be able to flexibly incorporate any future advancement made in the beam control and management technologies.

To support mobility for vehicular communication, 3GPP specifies that V2X technology is expected to support up to 250 km/h for high speed vehicles (up to 500km/h for trains) and to support ideally 0 ms of mobility interruption time (MIT) [14], [15]. Unlike an onmi-directional transmission, mmWave beams offer much narrower radiation footprint which causes handover events to occur more frequently for a fast moving UE. Supporting rapid and seamless handover will be necessary to avoid constant connection interruption. Handover decision making at the point of handover event needs to be not only fast but also smart to select an adequate beam for handover, which depends on both sufficient link quality and data availability [16].

Mobility management is extensively investigated in cellular networks at which mmWave was mostly overlooked due to very limited research by then [17]–[21]. However, there is a growing body of research on beam based mobility management in 5G and beyond cellular networks for vehicular communications. Thus, it is highly important and well timed to provide overview of the main aspect of beam based mobility management in the existing 3GPP 5G NR body, examine how beam based mobility is handled in 5G mmWave networks in the research body in context of vehicular mobility, and discuss potential emerging technologies that can further fuel the research of mobility management towards achieving the ambitious target of highly reliable zero interruption time handover for mmWave beam transmissions.

The remainder of this paper is structured as follows. Section II provides an overview and requirements for C-V2X communications. In Section III, we present the connected mobility in 5G NR in the aspect of cell-level and beam-level mobility for mmWave beams. With the introduction of mmWave beam based mobility management, in Section IV, we continue to discuss the challenges and issues with beam based mobility. In Sections V and VI, a survey of beam based mobility management enhancements are given, with Section V focusing on traditional approach and Section VI focusing on emerging machine learning technique. Finally, we draw our conclusion in Section VII with a summary of the future mobility management research trends for current 5G and beyond 5G (B5G). A complete organization of the paper of is given in Fig. 1.

II. V2X USE CASES AND REQUIREMENTS

Modern automotive industry continuously aspires to produce products that are increasingly more environment friendly, safer and more desirable to use [22]. Through automated driving, road accident could be significantly reduced, the flow of traffic can be improved, also the energy consumption of the automated vehicles can be minimised [23]. To automate driving, vehicles must be able to sense and understand their the surrounding environment in order to safely effectively control the vehicles motion without any intervention of humans. Various challenges in such applications need to be considered in order to successfully achieve the automated driving, such as:

- *Accurate and reliable localisation*, i.e., determining the relative or absolute position of the ego vehicle on the road.
- *Sensing and perception*, i.e., acquiring raw data about the surrounding environment and extracting semantic knowledge about what is surrounding the vehicle.
- *Control*, i.e., computation of collision free, energy efficient and comfortable trajectory of the vehicle and execution of those through vehicles actuators, e.g., steering angle and speed.

These functions are implemented through the use of various of sensor systems, such as cameras, radar, or laser range finders, and powerful computers that run sophisticated AI algorithms [24]. To achieve a level of safety that is superior

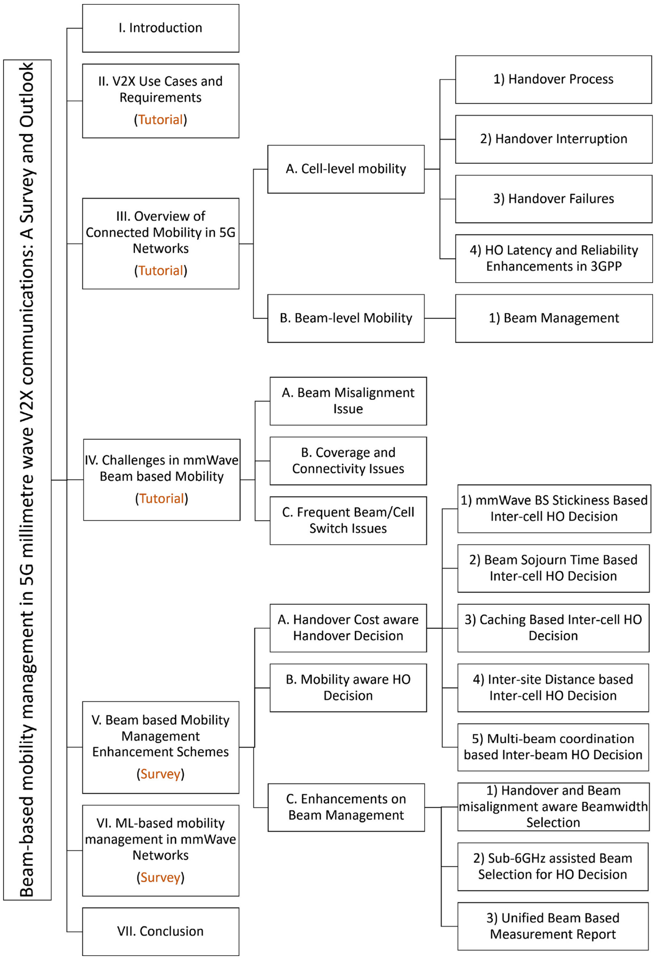

FIGURE 1. Structure and focus of this survey paper.

to that of human drivers, the components of the system, particularly, sensing system must be highly capable of collecting and delivering sufficient information to the AI algorithms at the heart of perception and control functions of the vehicle. However, on-board sensing can be inherently impaired (e.g., due to occlusions or sensor noise), particularly in complex road segments [25]. Therefore, effective fusions of off-board data through V2X systems can make a crucial difference in implementation of highly automated driving functions. For example, connected automated vehicles can periodically transmit the messages that are safety related and are concerned with its current condition to its neighboring vehicles, that can be crucial for all of the vehicles so that they could be able to effectively operate within the given region. V2X systems can also enable exchange of information among road users and infrastructure that can significantly improve the flow of the traffic, energy efficiency of the vehicle and the ride comfort for the passenger.

There have been two paradigms for enabling of connected automated driving, 1) through direct V2V communications, 2) through infrastructure - such as cellular networks. While each approach has its cons and pros, there seems to be a trend toward infrastructure based approach within the context of 5G systems. These are being developed on the basis of;

TABLE 1. List of acronyms.

Acronym	Name
3GPP	Third Generation Partnership Project
LTE/LTE-A	Long Term Evolution-LTE-Advanced
NR	New Radio
gNB	gNodeB
UE	User Equipment
AMF	Access and Mobility Management Function
UPF	User Plane Function
HetNet	Heterogeneous Networks
RLF	Radio Link Failure
HO-CMD	Handover Command
HOF	Handover Failure
ISD	Inter Site Distance
RSRP	Reference Symbol Received Power
RSSI	Received Signal Strength Indicator
TTT	Time-to-Trigger
MTS	Minimum-time-of-stay
RACH	Random Access Channel
MAC	Medium Access Control
RLC	Radio Link Control
PDCP	Packet Data Convergence Protocol
RRC	Radio Resource Control
V2X	Vehicle to Everything

- V2V: It allows communication between vehicles using cellular network. Vehicle can exchange information with other vehicle via direct communication or through the road side unit in case of insufficient direct link.
- V2I: it enables vehicles to exchange information with road side and cellular network. Vehicles can share their current status with road side unit and this information can be disseminated other vehicles supporting V2I.

3GPP community has introduced enhancements in cellular- based V2X support into consideration to meet stringent latency and reliability requirements of V2X applications. Due to current limitations of LTE to support ultra-low and highly reliable services, 3GPP has introduced 3GPP 5G support for V2X services in Rel. 15. The enhancements cover both safety and non-safety V2X services within present of LTE and 5G NR as well as other non-cellular based V2X providers. The key enablers of 5G for V2X would be automated driving, safety related services and efficient road conditions [6], [26]. However, these use cases and services require ultra-low latency (e.g., below 10 ms) and highly reliable (e.g., 0.001% maximum tolerable packet loss rate at the application layer) communication, which are summarised in Table 2, communication which current wireless networks are beyond to support [6].

To support aforementioned stringent vehicular requirements for high data transmission rates, millimetre wave (mmWave) has become one of the promising candidate for 5G systems due to inadequacy of available spectrum and high data rate support in the current sub 6GHz microwave bands. With the higher bandwidth and low latency potentials of mmWave access for vehicular communication, it can fuel the development of autonomous driving by supporting

TABLE 2. V2X use cases and requirements [8], [26].

Application	Description	Use Case	End-to-end latency(ms)	Reliability (%)
Vehicle Platooning	It supports vehicles travelling in same direction to form dynamic platoons. Latency and reliability requirements varies depend on distance gap between vehicles in group.	Automated cooperative driving for short distance grouping	10	99.99
Remote Driving	Remote driving allows a human operator or cloud to control vehicle remotely when remote action is required. Coordination between vehicles can be also possible when cloud computing is in control instead of human intervention.	Remotely controlled drive by human operators or cloud computing	5	99.999
Advanced Driving	It improves the accuracy of sensors' estimation through exchanging status information among vehicles to update trajectories or manoeuvres so that collisions and accidents can be avoided.	Cooperative Collision Avoidance (CoCA)	10	99.99
Extended Sensor	The idea is to extend the view and perception of vehicles through exchanging information provided by local sensors of other vehicles or road side units when local sensors are unable to detect due to obstacles and objects. In this case, vehicle can have such information through network when direct communication is not available.	Collective Perception of Environment	3	99.999

high data demands and latency-sensitive applications [4]. However, mmWave channel is very susceptible to mobility and blockages, which will be more exacerbated in automotive environment [5]. The 5G mmWave is a promising candidate for V2X, and the current development focus is to address the challenges of mmWave due to the high mobility vehicular scenarios [9].

Despite the benefits of 5G mmWave access, transmissions at such high frequencies ($\gg$ 6GHz) often suffer from high propagation loss. To counter the high propagation loss, mmWave transmitters focus the transmission power towards at a specific direction to provide a practical transmission range. The directional transmission in mmWave, often called a mmWave beam, however introduces new challenges in communications, and the most prominent issue is the aspect of mobility management, especially for vehicular communication when the user equipment (UE) is a moving vehicle. For the connectivity, there is a need for accurate beam alignment and connection robustness against rapid channel changes [10], [11]. Moreover, new solutions for timely switching of beams are needed in the case of high mobility vehicles [12]. While being connected, the UE will encounter two types of mobility in mmWave, namely the cell level and beam level mobility as specified in 3GPP Rel. 16 [3] which are discussed in the following.

III. OVERVIEW OF CONNECTED MOBILITY IN 5G NETWORKS

We shall discuss the mobility management of cellular networks focusing on the beam based mmWave transmissions in two levels: Cell-level mobility and Beam-level mobility. To better understand the terminology, descriptions of the key terms are given in Table 3.

A. CELL-LEVEL MOBILITY

Cell-level mobility requires handover process which initiates transferring of user session to a new cell when signal strength from current cell degrades. At this level, RRC signalling is explicitly involved in the process to identify a more appropriate cell and migrate the user to the identified cell. In the following, we shall overview the handover procedure and its issues, and discuss the existing 3GPP efforts to address those issues.

TABLE 3. Key terms and descriptions.

Key Term	Description
Cell-level mobility	the handover process where the user establishes a new connection to a new cell for better quality-of-service (QoS) [27]. **Synonyms**: inter-cell and inter-BS handover.
Beam-level mobility	a beam change/switch within the same cell coverage. **Synonyms**: inter-beam handover, beam switching.
Mobility Management	a process dealing with both idle-mode mobility and connected-mode mobility[1].
Handover Management	a process dealing with connected-mode mobility.
Beam Management	a set of operations for fine alignment of transmitter and receiver beams.
Beam Selection	a process involving beam sweeping and selection of the best beam for transmission.
Beamforming	a signal processing technique used in antenna arrays for directional signal transmission/reception
Beam pair	a pair of transmission beam and correlated reception beam.

1) HANDOVER PROCESS

Handover (HO) mainly happens due to degrading signal strength with serving cell when a UE moves away from the cell. When other neighboring cells can offer better signal strength than the serving cell, to avoid loss of connectivity, it is tactical for the UE to switch its connection to the cell that offers better signal quality. Handover in the current cellular networks is UE-assisted and network controlled. In other words, handover decision is performed by the source cell based on UE measurement. UE measurement should be met by certain criteria, for example, event A3 which states that "neighbor becomes offset better than serving" for a specific Time To Trigger (TTT) period as shown in Fig. 3.

As depicted in Fig. 4, when this criteria is met, UE first sends Measurement Report, and Source gNB initiates HO preparation phase which lasts until UE receives HO

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[1] Note that, we refer to connected mobility when we use mobility management in the rest of the paper. As idle-mode is not concern of this survey.

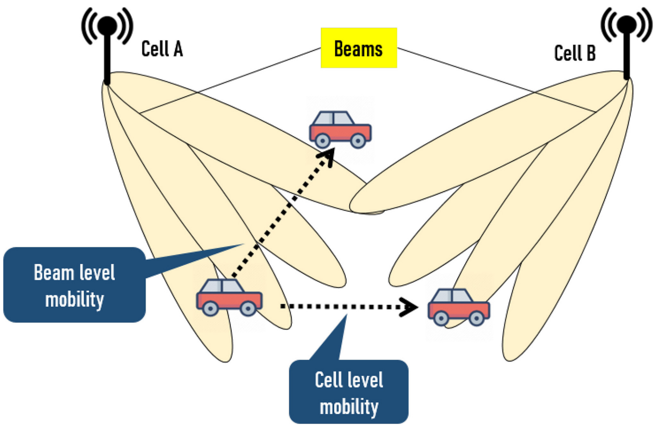

FIGURE 2. Cell-level and Beam-level mobility in directional mmWave Networks [28].

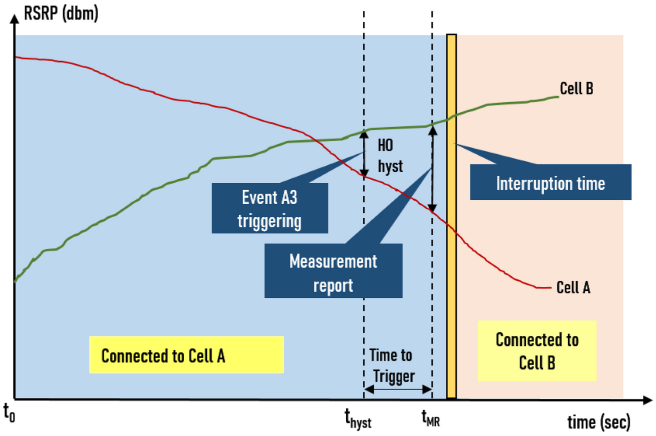

FIGURE 3. Event A3 based handover triggering.

command message, i.e., RRC reconfiguration. This is the beginning of HO execution phase where UE follows random access (RA) procedures to attach itself to Target gNB. Once Target gNB has RRC reconfiguration complete message from UE, it informs AMF/UPF to perform the path switch. Finally, Target gNB informs Source gNB to release UE context related resources.

2) HANDOVER INTERRUPTION

From the handover process described above, we can see that UE may face a handover interruption time (HIT) in which the UE has no longer an active data connection with network during the execution phase. This is mainly because upon receiving HO command, the UE must release the data connection with Source gNB. This HIT lasts until the communication with network is resumed through Target gNB, which can take tens of milliseconds, and some case even a disconnection due to failing to resume a connection through Target gNB. We shall continue our discussion of handover failure in the following.

3) HANDOVER FAILURES

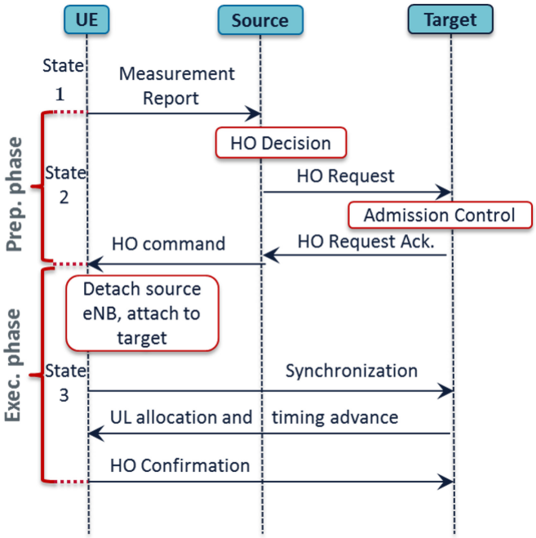

FIGURE 4. Handover signalling process [3].

Handover failure (HOF) is one of the main key performance indicators (KPIs) in handover operation, as handover failure causes loss of a connection which directly impacts user experiences. Handover failure mainly happens due to the occurrence of the radio link failure (RLF) during handover process, and thus detecting radio link problem during a handover is important. In order to detect a radio link problem during handover, timer based handover failure is supported in 5G NR. When handover is initiated by the network, UE may experience handover failure if RLF occurs after timer expiry before UE receives handover command. Even though RRC reconfiguration message is received successfully, UE can still face HOF when RLF occurs before RRC reconfiguration complete message reaches to Target gNB. These HOF scenarios during handover process is depicted in Fig. 5. In case of a HOF, UE initiates RRC connection re-establishment procedure with one of the cell. UE re-establishment upon RLF occurrence can also indicate whether handover happened at the right time and to the right cell. In this regard, three cases are possible to classify handovers based on HOF as shown in Fig. 6, which are described below.

- *Handover being too late:* A RLF occurs before HO or during HO; UE re-establishes the radio link with the target cell.
- *Handover being too early:* A RLF occurs after HO or during HO; UE re-establishes the radio link connection in the source cell.
- *Handover to a wrong cell:* If UE re-establishes the radio link connection in a different cell (neither source nor target).

4) HO LATENCY AND RELIABILITY ENHANCEMENTS IN 3GPP

We shall introduce two prominent attempts from the 3GPP standard to illustrate the efforts in improving HO in 5G NR. The first attempt is to address the potential interruption issue during handover and the second is to address the handover failure.

Until 5G NR Rel. 15, handover process follows *break-before-make* handover, where a UE disconnects from the

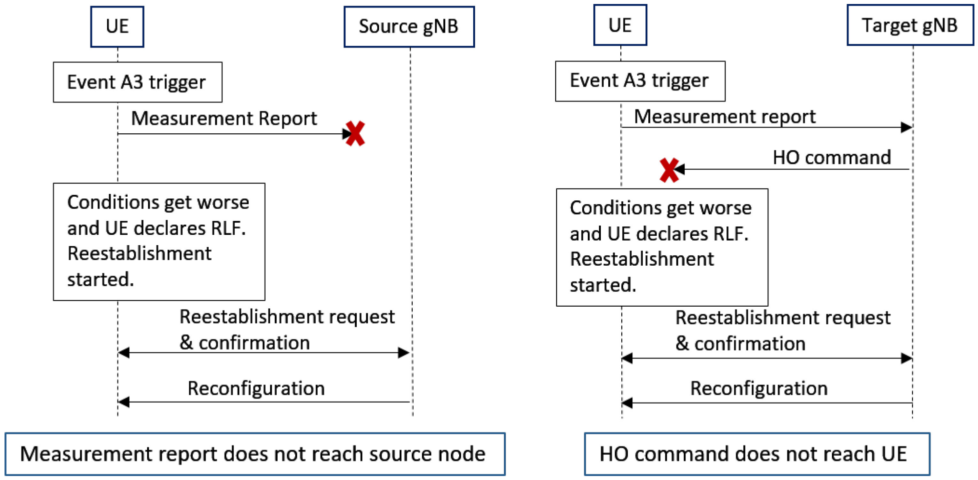

FIGURE 5. Mobility related failures during HO process.

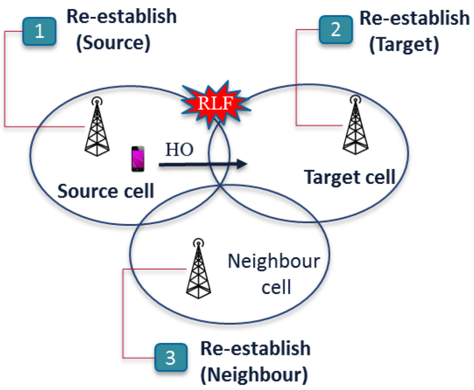

FIGURE 6. Classification of handovers based on UE re-establishment.

TABLE 4. Comparison of the mobility enhancements considered by 3GPP [29].

Solutions	Description	HO Interruption	Comments
LTE baseline HO	Conventional handover.	∼50ms	
Make Before Break (MBB)	Source link is maintained until RACH preamble transmission in the target starts	∼30ms	Part of LTE Release 14
RACH-less HO	Handover without RACH in the target cell.	∼20ms	Part of LTE Release 14
MBB + RACH-less	Source link is maintained until the first PUSCH transmission starts at target	∼5ms	Part of LTE Release 14
Dual-connection based mobility	Simultaneous connections with source cell and target cell are maintained.	∼0ms	Specified as Dual Active Protocol Stack (DAPS) handover in NR Release 16 [3]
UE based HO	Handover command is provided earlier (when source channel quality is still good) and UE decides when to perform handover.	∼50ms	Specified as Conditional Handover in NR Release 16 [3]

source cell upon receiving handover command without waiting for the establishment of a new connection with the target cell. The interruption time after breaking existing before making a new connection can lead to delay which is unfriendly to some use cases and applications targeted to support by 5G, such as the ultra-reliable and low latency communication (URLLC). As given in Table 4, typical handover execution time is about 50 ms with break-before-make handover. In case of handover failures, the connection re-establishment increases the data interruption time up to about a few hundred milliseconds and even several seconds [15]. To avoid such interruption time, 3GPP considered a new approach to allow UE to continue communication with the source cell until a new connection is finalized at the target cell. This requires the UE to simultaneously receive and send data from/to both the source and target cells during handover execution time. To allow such capability, a new solution called *Dual Active Protocol Stack* (*DAPS*) handover is proposed by 3GPP in Rel. 16 [3]. With DAPS, a UE shall 1) continue to user data transmission/reception to/from Source gNB upon HO command; 2) concurrently receive user data from Source and Target gNBs during handover execution period; 3) change UL transmission point for user data as Target gNB upon completion of random access process. The operation of DAPS is demonstrated in Fig. 7. To support the feature, a UE builds a separate protocol stack for Target gNB, including RLC, MAC and PHY layers. Thus, unlike the *break-before-make* HO, the UE will not reset user plane protocol stack for Source gNB to ensure that it can continue the transmission and reception of user data.

Note that, when user needs connection re-establishment due to handover failures, the total interruption time including HIT is named as mobility interruption time (MIT) which is defined in [14] as; “the shortest time duration supported by the system during which a user terminal cannot exchange

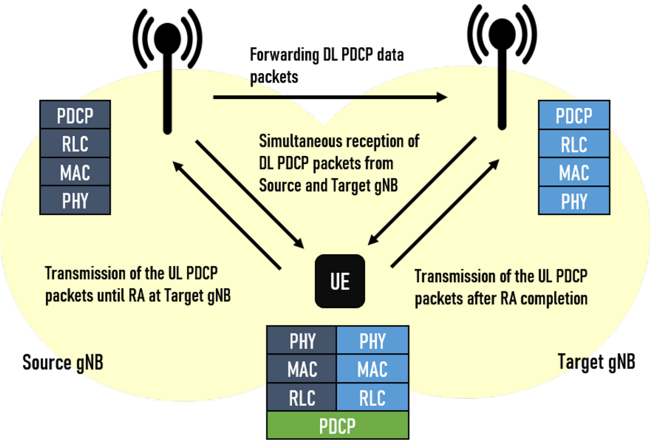

FIGURE 7. The concept of DAPS Handover [3].

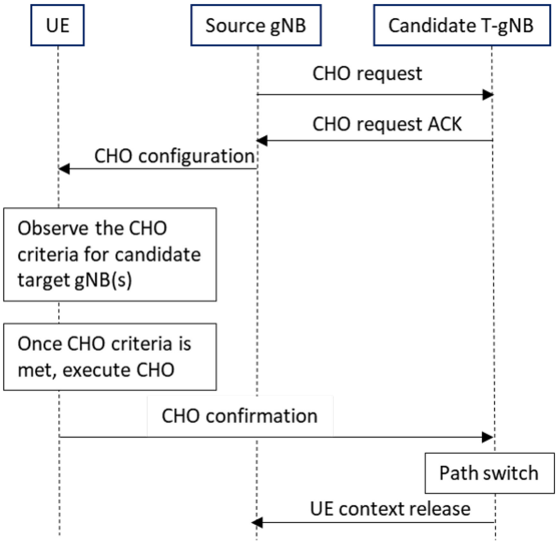

FIGURE 8. Conditional Handover process [3].

user plane packets with any base station during transitions". Thus, despite 0 ms HIT is possible with DAPS as shown in Table 4, the following solution is proposed to improve mobility robustness by reducing handover failures and additional mobility interruption time due to connection re-establishments.

Conditional Handover (CHO) is introduced and standardized as part of Rel.16 to address the handover failure issue [3]. CHO aims to control and modify handover process to reduce mobility related failures. In CHO, unlike the legacy handover, a UE will not act immediately upon receiving HO command while signal conditions are still considered good for receiving an HO command. Instead, it will buffer the HO command and act upon when certain conditions are met. These conditions can be configured by the network, for example when a neighboring cell becomes offset better than the source cell. Once conditions are satisfied, the UE acts upon previously buffered HO command instead sending a measurement report and waiting for the HO command to minimise the risk of the signal failure. This process is depicted in Fig. 8.

The source cell can also prepare a set of candidate cells for CHO due to uncertainty in handover execution to one of the prepared cells as Target gNB. Upon completion of handover execution at Target gNB, Source gNB will be informed to release the reserved resources for other candidate cells.

B. BEAM-LEVEL MOBILITY

Beam-level mobility happens when a UE performs beam change or switch within the same cell as shown in Fig. 2. Unlike the cell-level mobility, beam-level mobility is handled internally within a cell, so involvement of PHY and MAC layers will be sufficient to complete the task [3]. This has the benefit of not including the heavy RRC operation.

Since the mobility management is done within a cell, it is often discussed as management of the low level beam operations rather than a handover, although the operation can be seen as a handover from a beam to another. In the following, we shall focus on discussing the beam management for beam-level mobility.

1) BEAM MANAGEMENT

As aforementioned, beam-level mobility is more closely related to beam management which is different from the commonly known mobility management in cell-level mobility. Beam management aims to maintain the connectivity of a UE within a cell by serving the UE with a beam that can deliver better link quality to the UE. In case of a dropping link quality due to, such as UE mobility, through beam management the cell can quickly reconfigure the existing beam for improved link quality or switch to another beam if necessary. Beam management process generally involves in certain aspects of establishment and maintenance of beams for the UE within the serving cell [30].

For completeness, we shall briefly describe the aspects of beam management in the following. Further details of the beam management procedures can be found in [13], [31], [32].

- **Beam determination:** Selection of beams for the communication between gNB and UE.
- **Beam measurement:** Measuring the features of the received beam signals for gNB or UE.
- **Beam reporting:** Reporting information about a beam signal for UE based on beam measurement.
- **Beam sweeping:** Covering a spatial area by transmitted and/or received beams for a certain period in a predefined way.

IV. CHALLENGES IN MMWAVE BEAM BASED MOBILITY

Ideally, beam based mobility should support a rapid beam or cell handover to combat rapid signal degradation in mmWave communication. Additionally, UEs should be able to utilise multiple overlapping beams as alternative communication

TABLE 5. Beam-based mobility challenges.

Challenge	Ref
Beam Misalignment Issue	[27], [34]–[37]
Coverage and Connectivity Issues	[10], [27], [35]–[41]
Frequent Beam/Cell Switch Issues	[10], [27], [34]–[37], [39], [42]–[44]

links to improve the reliability. To achieve rapid handover, the handover design should have minimum signalling overhead on the RRC layer.

It is shown in [33] that SINR (Signal-to-Interference-plus-Noise Ratio) can suddenly (within around 5 to 10 ms) drop over 20 dB due to shadowing. This sudden signal deterioration is indispensable at high mmWave frequencies. The impact can be more significant in case of mobility related signals such as measurement reports or handover commands are transmitted over these beams. The main objective of the connected mobility is to ensure the continuity of user connection. To achieve this, continuing research is needed which may include advanced algorithms for decision making and alternative network architectures for more efficient mobility management.

An effective approach to address the high mobility in cellular network is to offer a large radiation footprint to UEs. Unfortunately, the use of mmWave beam offers the opposite of a small and narrow radiation footprint which poses challenges to the maintenance of the connectivity. Beam based mobility solution will require an efficient beam setup and establishment which is highly dependent on beam alignment issue [10], [11]. Besides, the solution must provide adequate coverage from a collection of narrow beams. Finally, it should achieve fast switching between beams in case of high mobility vehicles to maintain connectivity [12]. In the following, we shall discuss these three issues in line with the literature as categorised in Table 5.

A. BEAM MISALIGNMENT ISSUE

Misalignment between transmitter and receiver is most likely to occur with narrow beamwidth, especially in a network with high mobility UEs. One limit arises from the hardware related limitation, such as antenna technology and signal processing capability. The limitation will lead to imperfection in beam measurement and initial alignment. Besides, due to fast moving UEs and rapid changing channel conditions, tracking of UE movement for beam realignment and adjustment may be delayed [4]. As reported in [35], beam misalignment probability is also highly dependent on the UE moving speed, time duration between two periodic synchronization signal burst (SSB), and average distance between two beam (re)selections. In a vehicular network, the speed of UE is the dominating factor.

B. COVERAGE AND CONNECTIVITY ISSUES

The authors in [38] proposed a stochastic geometry model to analyse beam coverage and connectivity performance in mmWave vehicular networks on a highway scenario. The work concluded that the connection stability depends on both beam alignment and sufficient signal quality. Connectivity probability can be improved with narrow beams when base station density increases in a sparse network. However, this probability degraded with increasing of base station density in dense networks. Hence larger footprints of beams should be used to provide more robust alignment. To improve connectivity and rate, frequent beam alignment actions are needed to reduce disconnection time due to misalignment between end points. They show that the performance of the vehicle communication is highly dependent on the periodicity of beam alignment, vehicle speed, beamwidth and BS density.

C. FREQUENT BEAM/CELL SWITCH ISSUES

Dense deployment of mmWave cells and using narrow beams to mitigate propagation loss effect will escalate the number of cell-level (inter-cell) and beam-level (intra-cell) handovers, which can limit the performance gain [42]. Handover problem is doubled by inter-cell and inter-beam handovers when beam based communication in mmWave is considered. There are more entities involved in the handover decision making, coupled by various beam radiation footprints which makes the design for a handover solution for beam based mobility much more complex than the traditional solution. Hence, new techniques and analytical approaches are required to investigate beam-aware handover performance.

Narrow coverage and high density of mmWave cell can lead to both frequent handovers and beam switch, as the study in [10] has confirmed that frequent handover in directional mmWave networks is a more apparent problem as compared to the omnidirectional networks. To support the continuity of the communication, frequent beam alignments needs to be performed to reduce disconnection time due to misalignment between end points [38] as vehicle moves.

V. BEAM BASED MOBILITY MANAGEMENT ENHANCEMENT SCHEMES

In this section, we shall provide an overview of proposed beam based mobility management enhancement schemes for mmWave communication in 5G network in the current research efforts. A summary of our overview is also given in Table 6.

A. HANDOVER COST AWARE HANDOVER DECISION

As discussed in Section IV, the BS density plays an important role in providing the network coverage. Having high BS density also introduces complexity in the handover operation since the multiple BSs can now provide services to the same area. Conventional received signal strength (RSS) based handover mechanism leads to high number of beam/cell changes. When considering data interruption and signalling overhead during each handover, the total handover cost increases manyfold in dense mmWave networks. Thus, it becomes crucial to reduce the need for excessive number of handovers by selecting long lasting connections in the events of handover decision.

TABLE 6. Beam based MM schemes in mmWave.

Ref	Scheme	Network Topology	MM type	HO Delay (ms)	mobility	Blockages
[42]	mmWave BS stickiness based inter-cell HO decision	dense mmWave cellular networks	inter-beam and inter-cell	700 (ICH), 350 (IBH)	street movement (up to 30m/s)	×
[45]	Multi-beam coordination based inter-beam HO decision	continuously arranged beam (CAB) system	inter-beam	—	straight movement (16.7 m/s)	×
[44]	Multi-beam coordination based Inter-beam HO decision	mmWave only	inter-beam	200 (IBH)	high speed railway 500km/h	×
[34]	Handover and beam misalignment aware beamwidth selection	mmWave HetNets	inter-cell (μW-mmW)	100-500 (ICH)	Gauss-Markov mobility based	✓
[39]	Caching based inter-cell HO decision	mmWave HetNets	inter-cell (μW-mmW)	—	random direction (3km/h - 60km/h)	✓
[10]	Beam sojourn time based inter-cell HO decision	mmWave HetNets	inter-cell (μW-mmW)	$N(20, 1)$ (HIT)	Gauss-Markov(GM) mobility	×
[46]	ISD based inter-cell HO decision	mmWave HetNets	inter-cell (μW-mmW)	50 (HO preparation), 40 (HO execution)	straight line (60 km/h)	×
[43]	Beam sojourn time based inter-cell HO decision	dense mmWave only	inter-beam and inter-cell	[700, 350] (ICH), [350, 175] (IBH)	straight line (20 m/s - 40 m/s)	×
[35]	Handover and beam misalignment aware beamwidth belection	dense mmWave only	inter-cell and inter-beam	43 (ICH), 23 (IBH)	straight line [3, 30, 120] km/h	✓
[27]	Unified beam based measurement report	UDN mmWave only	inter-cell and inter-beam	—	uniform movement (16.7 m/s)	×
[47]	Multi-beam coordination based inter-beam HO decision	mMIMO mmWave	inter-beam	0 (IBH)	straight line (360 km/h)	×
[36]	Mobility aware HO Decision	mmWave only	inter-cell	—	urban scenario [10, 15, 20] km/h	✓
[37]	Mobility aware HO Decision	mmWave HetNets	inter-cell (μW-mmW)	100-500 (ICH)	Gauss-Markov mobility based	✓
[41]	Sub-6GHz assisted Beam Selection for HO Decision	mmWave HetNets	inter-cell (μW-mmW)	—	fixed direction	×

1) MMWAVE BS STICKINESS BASED INTER-CELL HO DECISION

Considering a dense mmWave cellular networks, the authors in [42] derived an analytical model for inter-cell handover and inter-beam handover rates using stochastic geometry to investigate the impact of mmWave BS density and handover stickiness on inter-cell handover (ICH) and inter-beam handover (IBH) performance. ICH and IBH rates, along with handover delay, each handover is used to calculate total handover cost in terms of unit time. Relatively lower delay value assumed for IBH than ICH. It is found that both ICH and IBH rates are proportional to user velocity and the square root of handover stickiness. Based on their study, both ICH and IBH rates tend to increase with increasing BS density and user speed while both rates decrease as handover stickiness increases. Handover stickiness helps to retain a user in the current BS, and hence this reduces the number of handover events. The proposed scheme, considering handover stickiness variable as 1.6, starts to outperform the strongest BS selection scheme in terms of average spectral efficiency (ASE) at near velocity 20 m/s with BS density $\lambda = \frac{1}{40^2\pi}\mathrm{m}^{-2}$. The authors also show relation between handover stickiness and ASE, and the results show a trade-off between ASE and handover stickiness degree. ASE increases as handover stickiness degree increases to a certain point, and then starts to decrease for further higher stickiness levels. This outcome suggests that an optimal setting of handover stickiness level exists. Note that, inter-cell and inter-beam handover delay is assumed, respectively as 0.7 and 0.35 sec. As this values are based on conventional LTE networks [48]. For better evaluation, analysis should be performed with lower delay assumptions considering current cellular networks.

2) BEAM SOJOURN TIME BASED INTER-CELL HO DECISION

Narrow beams lead to short beam sojourn time which results in limited time to perform channel estimation, power control and link adaptation. This is especially critical under high mobility scenario [35].

In [43], a beam sojourn time based handover decision is proposed to minimise the chance of handover events when a vehicle travels in densely deployed mmWave network. The authors develop an analytical model to find theoretical upper-bound for beam sojourn time, when a BS offering the longest beam sojourn time is selected for handover. The theoretical upper-bound is also used to benchmark the performance of any practical design and is adaptable to various assumptions, such as number of beams per cell and beamwidth. Relative location and direction of travel of a vehicle are utilised to design a Fuzzy Logic (FL) based beam-centric distributed algorithm to determine the beam among all visible beams where a vehicle can achieve the longest displacement within it. The authors then design a FL based distributed algorithm that utilises the instantaneous mobility information to determine the BS with longest beam sojourn time. For performance evaluation, simulation based ICH and IBH rates are used to calculate the handover cost in unit time. With the strongest signal based handover scheme, almost 90% of sojourn times are less than 1.25 seconds where it is less than 20% in FL-Based solution and nearly 5% for the upper-bound results with velocity of 20m/s. FL-Based solution also shows significant gain up to 33% and 70%, respectively, in terms handover cost and overall throughput compared to the strongest cell based scheme with velocity of 40m/s, and ICH and IBH delays of 0.7 sec and 0.35 sec respectively. Note that the work also evaluates the performance with lower delays of 0.35 sec and 0.125 sec for ICH and IBH, respectively, but results show relatively lower gains in throughput.

Focusing on connection robustness, an effective beam coverage probability (EBCP) based handover scheme in mmWave heterogeneous network to improve connection robustness is presented in [10]. EBCP is adopted as a handover decision criteria along with hysteresis and TTT values. It was shown that handover frequency rate is decreased compared to traditional RSRP-based scheme at the cost of throughput. Handover frequency rate is decreased by 35% for 20 m/s and 11% for 5 m/s as compared to traditional RSRP-based scheme at the cost of 4% and 1% throughput respectively.

3) CACHING BASED INTER-CELL HO DECISION

The work in [39] considers a HetNet which are composed of a macro BS (MBS) and dual-band small BSs (SBSs) capable of both mmWave and microWave band. The authors proposed an energy efficiency aware handover mechanism by reducing inter-BS handovers through utilising caching capability of mobile users in mmWave band. The need for handover to a new BS can be avoided by playing cached video content for some time. By considering limitations on the cache size, energy consumption and HOFs, each user can make adaptive decisions whether to handover a new SBS, connect to a macro BS, or use cached content to skip HO. It is found that high mobile users are more likely to skip target MBS or use their cached content when user residence time in SBS is small. The results show significant reductions in inter-frequency scanning, the number of handovers and also energy consumption. By utilising cached segments and skipping unnecessary cell search, numerical results show that the proposed solution achieves up to 80% and 29% savings in energy consumption, respectively, for mobile speeds of 8 m/s and 12 m/s. The proposed scheme also achieves nearly 45% reduction in the average HOF, for mobile users with velocity of 60km/h.

4) INTER-SITE DISTANCE BASED INTER-CELL HO DECISION

In [46], the impact of inter-site distance (ISD) between a macro BS and a mmWave BS on HO performance is analysed. Probabilities of handover and handover failure are formulated by closed-form expressions. The work shows that an entering point to a sector of mmWave cell and inter-site distance between the macro BS and the mmWave BS have an impact on handover performance. The results show that HO probability decreases as TTT increases or/and distance decreases. It is also found that using a longer TTT value (i.e., 320 ms) for short inter-site distances (i.e., less than 50 m) minimises handover failure probability. This is because mmWave coverage, which is defined as the area where the mmWave cell signal is stronger than macro cell signal by at least of hysteresis value, becomes smaller when inter-site distance increases, and hence with a longer TTT, UE is more likely to be out of coverage of the mmWave cell. On the other hand, when a shorter TTT is used for a long inter-site distance, lower handover failure probability is observed.

5) MULTI-BEAM COORDINATION BASED INTER-BEAM HO DECISION

The problem of signalling overhead due to frequent inter-beam handovers mmWave communication is addressed in [44], [45]. The work in [45] considers continuously arranged beam (CAB) system where multiple beams are arranged in fixed directions and beam switching within same BS is treated as handover. The work adopt two approaches to improve inter-beam handover performance. The former one considers coordinated scheduling for inter-beam handover enhancement. The latter uses small size low layer messages, i.e., the size of handover messages are down to 4 bytes from 14 $\sim$ 36 bytes used in LTE HO based IBH scheme, where control messages are exchanged at MAC layer, to minimize signalling overhead. This avoids the need for exchanges of some large size messages in the conventional HO at RRC layer. Numerical results show that, compared with the conventional LTE HO based IBH scheme, the proposed scheme can reduce the handover failure rate by up to 95% depending the distance from beam centre line and the threshold of signal strength. The proposed scheme also reduces the signaling overhead by 78% and 92% in uplink and downlink, respectively.

In [44], a inter-beam handover class (IBHC) is proposed to reduce frequent inter-beam handovers, in which multiple beams are grouped in according to mobile user movement route and inter-beam handover frequency. In the proposed IBHC scheme, multiple beams in the same group are synchronized and allocated with same amount of radio resources. Mobile users decide its IBHC level based on velocity and inter-beam handover rate so that it does not perform handover for each beam inside the same group. In other words, received signals from different beams in the same group are treated as the same signal. Depending on IBHC level, inter-beam handovers can be performed for up to every four beams instead of every beam with improved SINR due to coordinated transmissions while supporting high mobility ($>$ 300km/h) in mmWave, hence total time wasted by handovers is reduced in proportion to IBHC level. Note that, the proposed scheme is based on duplicated resources at adjacent beams, hence evaluation of the scheme is needed when available resources are insufficient due to congestion.

To improve reliability of the inter-beam handover while using resources efficiently, [47] proposed a multi-beam cooperation algorithm to jointly reduce inter-beam handover failure rate and resource occupation rate for high speed train (HSR) in 5G mmWave networks. In the proposed scheme, serving beam group is created with specific number of beams based on UE's speed and location, and available resources. Seamless inter-beam handover mechanism is adopted while adding a new beam or removing the old beams in the serving beam group. Simulation results show that the proposed scheme outperforms conventional LTE IBH in terms of handover failure rate and reduces beam resource occupation rate up to nearly 50% as compared to IBHC scheme.

B. MOBILITY AWARE HO DECISION

Mobility aware user association problem is designed to overcome the limitation of conventional RSS based BS selections. The proposed optimisation algorithm in [36] is able to 1) elaborate the mobility induced dynamics in the network and channel conditions, 2) mitigate the frequent handovers, and 3) incorporate mmWave features such as directional and sensitivity to blockages. By observing the results, the proposed scheme shows significant gain compared to RSS based association when velocity and association period is high. For example, proposed scheme provides seven times higher achievable data load than the one achievable by the RSS based association when association period lasts 10s and velocity is 20 km/h.

The authors in [37] proposed a Markov decision process (MDP) and Gauss-Markov mobility model based mobility-aware handover algorithm, utilising user velocity, location and SINR, and mmWave cell dwell time to optimise handover performance. The work formulates handover decision as a Markov decision process. MDP based HO optimisation also considers beam alignment signalling overhead and blockages in the design. The authors show significant improvement in data rate by MDP based handover optimisation even under high mobility as compared to traditional signal strength based handover decision. For example, numerical results show that the handover cost weight approaches 10^9 unit utility per handover, the performance of SNR scheme falls below 0.5×10^9 (unit utility per bit) even becomes zero as handover cost increases further. In contrast, the proposed MDP scheme shows better performance in terms of total reward for all handover cost and velocity modes and settles at $1 \sim 0.5 \times 10^9$ when handover cost is 10^{10}. This is because MDP scheme decides to stay connected to macro BS and not to make handover to mmWave BS when handover cost becomes extremely high.

C. ENHANCEMENTS ON BEAM MANAGEMENT

mmWave heavily relies on beam management procedures to select the appropriate beam during BS handover (inter-cell mobility) and beam switching (intra-cell mobility) in a quick manner to avoid any beam misalignment or beam/link failure. Beam based mobility performance highly depends on solving the trade-off between various factors, such as speed of the mobile terminal, number of beams, beamwidths and cell size.

1) HANDOVER AND BEAM MISALIGNMENT AWARE BEAMWIDTH SELECTION

In [35], the authors provide a stochastic geometry based analytical model considering sector based antenna model for beam management in 5G. In this regard, beam selection for handover (inter-cell) and beam re-selection (inter-beam) probabilities are derived by considering Poisson Voronoi tessellation based user association. By increasing number of beams per cell, i.e., decreasing beamwidth, misalignment probability increases as mobile terminal (MT) is more likely to leave the current beam until new SSB measurement. Area spectral efficiency (ASE) is shown for different number of beams per cell and MT speeds in both FR1 (3.5 Ghz) and FR2 (28 Ghz). It is found that there is an optimum value of number of beams per cell which maximizes effective ASE since high number beams per cell can increase time overhead due to beam (re)selections which dominate beamforming gain.

In [34], a MDP based vertical handover decision scheme in mmWave HetNets is proposed to optimise user experience by taking handover cost and beamforming misalignment into account. Optimal beamwidth in mmWave cell is obtained by observing a trade-off between directivity gain and beam misalignment. The numerical results show that when handover cost[2] and mobility is both high (respectively, 10^{10} unit utility per handover and 4m/s) only the macro BS is connected. To avoid high computational complexity, an action elimination method which eliminates suboptimal actions from the action space is adopted. It is shown that, when compared to conventional value iteration algorithm, the proposed value iteration algorithm with reduced action space algorithm reduced (VIA-RAS) reduces computational complexity by $\frac{M|\mathcal{B}_s|}{4}+\frac{M}{4(M-1)}$ times where M is the number of base stations and $\mathcal{B}_s$ is the number of beamwidth options for mmWave beamforming.

2) SUB-6GHZ ASSISTED BEAM SELECTION FOR HO DECISION

Deafness issue in mmWave due to directional transmission leads to additional space search procedure that MT and BS need to perform to detect the presence of each other. While mmWave cells are deployed with conventional microwave band cells (sub-6GHz) to maintain robust connectivity [41], due to rapid channel variations and high vulnerability to blockages in mmWave band (> 10 GHz), sub-6GHz cell which can provide a wide coverage can be utilised for the preparation of beam selection for UE handover. In [41], the authors proposed an UE uplink measurements based mmWave BS (mmBS) selection. UEs periodically broadcast directional sounding reference signal (SRS) through whole angular space. By exhaustive search for beam steering, each mmWave BS collects corresponding SINR values for each beam direction to build SINR table which then shared with the macro cell. Based on SINR tables from each secondary cell, the macro cell decides the optimal mmBS and beam direction for each UE to connect. Handover is triggered upon different mmBS selection based on the SINR table. Since handover may not be performed based on the strongest

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[2] The handover cost weight ranges between 10^8 to 10^{10} units of utility for different combinations of handover interruption time (100-500 ms) and downlink data rate in 5G (1-20 Gbps).

cell, various information are required to account sophisticated handover decision problems. Note that this can brings complexity and extra delay. Moreover, this approach uses centralised decision making process which can become bottleneck, especially when the number of users and mmBS are large. Thus complexity and delay performance of such approaches should be further investigated.

3) UNIFIED BEAM BASED MEASUREMENT REPORT

The authors in [27] propose a new unified measurement event to trigger both beam-level (beam switching) and cell-level mobility (handover) based mobility management scheme in standalone 5G mmWave mMIMO system. In addition, the authors also designed a finite-state-machine (FSM) for user's mobility state to evaluate mobility performance, which is used to conduct Monte Carlo SLS to mimic the practical 5G NR system. To evaluate the proposed mechanism, several performance metrics such as RLF rates, signalling overhead, SNR and accuracy in beam pairing are considered. The simulation results show considerable improvement by achieving low RLF rates, better beam pairing, lower overhead compared to two conventional beam management schemes [32], [45]. With the proposed scheme, in the UDN scenario,[3] RLF probability rate is halved, beam switching failure probability is down to almost zero from 0.01 and 0.04 and HOF probability is reduced to 0.005 from 0.05 as compared to the other two schemes. Furthermore, the proposed scheme achieves less signalling overhead which is respectively nearly a half and one-fourth of the other schemes.

VI. ML-BASED MOBILITY MANAGEMENT IN MMWAVE NETWORKS

Recently, machine learning (ML) has attracted increasing interest in the design and optimization of wireless communication systems [61]. Particularly, in V2X networks featured by high mobility, heterogeneous connectivity, and diverse QoS requirement demands, ML is expected to be a promising tool to handle the complex problems that are difficult to describe by mathematical approaches or to be solved with conventional optimization mechanisms [62]. By utilizing several information available in V2X networks such as vehicle kinetics (e.g., speed, direction, acceleration), road conditions, and traffic flows, ML is applicable about various operational aspects of V2X for *adaptive data-drive decisions* [63].

For *beam management* of mmWave V2X networks, ML applicability is now being investigated in literature [64]. While the use of mmWave bands requires the beamforming and massive MIMO technologies, accurate beam alignment becomes indispensable. When BSs select beams to serve vehicles, their surrounding environment should be considered in order to avoid any blockages in LOS paths. In today's network, onsite signal measurements method (e.g., wardriving tests) is being used, but this conventional approach is time-consuming and unscalable for dense network deployments [65]. Considering highly-dynamic V2X networks, a dynamic beam management method (i.e., beam selection and beam alignment) which adapts to environment changes is essential. In addition, as aforementioned, frequent beam changes will be resulted by high mobility. Since beam switching can degrade communication reliability, proactive switching could be considered to guarantee seamless connectivity. Actually, identifying the optimal beamforming vectors in large antenna array of mmWave systems requires training overhead, one of the critical challenges to use the mmWave bands [66]. Although the beam switching for a phased-array antenna can be carried out almost instantaneous (50 ns) [67], increase in training overhead caused by beam switching results in the beamforming delay [68]. In order to make data-driven decisions by analysing information about vehicle movement and surrounding environments as well as channel quality, ML is applied to find best beams [49], [50], to manage beam switching [51]–[53], and to alleviate the training overheads [54]–[58]. Moreover, ML is adopted to effectively coordinate BS and intelligent reflecting surface (IRS) [59] and to manage increase of computational complexity of UE-BS association in a scenario of multiple moving UE and multiple BSs [60]. The approaches proposed in literature are summarized in Table 7.

In [49], ML-based *beam selection* algorithm is studied for a V2I network where a fixed RSU communicates with multiple moving vehicles. As a learning agent, the RSU predicts the optimal beam vector by using the obstacle information from locations and types of blocked vehicles (e.g., car, truck, bus). Although the deep learning approach is included in this paper, the main focus is to illustrate the flexible mmwave MIMO channel data generation methodology to facilitate ML-based approaches in the complicated mobility scenario, not to study a specific ML method. In [50], vehicle's direction of arrival is exploited to identify the traffic loads and a mmWave BS autonomously learns the data rate of every beam to identify the best beams over dynamic changes in traffics and environments (including permanent and temporary blockages) over time. While the beam selection is modelled as a multi-armed bandit (MAB) problem, the proposed approach is emphasized by the benefits of low-complexity and scalability. Especially, fast adaptation is highlighted as the benefit of the proposed algorithm. It shows the proposed ML approach enables mmWave BSs to gain near-optimal performance on average within 33 mins of deployment by context-aware learning. Moreover, for a given environment changes (i.e., blockage, traffic), the proposed approach is proven to remain within 5% of the optimal performance by prompt adaptation to environments.

The *proactive handover management* of mmWave bands is investigated by using ML to aim to minimize link disruption and signalling overhead in [51]–[53]. Firstly, the fact that identification of exact UE's location would be difficult is considered in [51]. The authors correlate the UE's location to received SNR values from all BSs. While existence

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[3] 50 gNBs are deployed in 0.1×0.1 km^2 area, and each gNB has 3-sectors; i.e., 3-cells. Each cell has 6-candidate beams.

TABLE 7. Summary of ML-based beam mobility management approaches.

Ref	Scenario	Objective	Contexts	ML technique	Learning agent
[49]	Beam selection of RSU to serve multiple vehicles	to max the effective channel gain	Vehicles' location and type	Deep Q-Networks	RSU
[50]	Selection of beams among a set of distinct orthogonal beams of a BS to serve multiple vehicles	to max aggregate network capacity	Vehicle's direction of arrival	Multi-armed bandit	mmWave BS
[51]	BS selection for handover decision in dense mmWave networks	to min the number HOs with improved user QoS	SNR and user trajectory	Double DQN	HO controller
[52]	BS selection for proactive handover to serve one UE	to min the prob. of session disconnection	Historical beamforming vectors and the hand-off status	DL	mmWave BS
[53]	Beam hand-off in high mobility 5G mmWave networks	to max data rate and reduce disconnection time by beam hand-off prediction	Mobility information (ue location and velocity), SNR, current beam index	DL	5G gNB
[54]	Prediction of beamforning vectors at distributed coordinating BSs to serve a UE simultaneously	to max effective data rates	Uplink training signals	DL	a central processing unit
[55]	A dual-mode communication system having both low-frequency and mmWave wireless links	to enhance reliability and reduce training overhead	Low-frequency channel information	CNN learning	mmWave BS
[56]	Beam selection of mmWave gNB in a single cell of sub-6GHz gNB	to improve beam selection accuracy (spectral efficiency)	sub-6GHz channel information	DNN learning	a central unit
[57]	Beam selection of a dual-band BS (supporting sub-6GHz and mmWave bands) for a UE	to improve beam selection accuracy	sub-6GHz channel information	DNN learning	BS
[58]	Target mmWave RRU prediction/preparation for handover decision for V2I communication in C/U-plane decoupled HetNet (sub-6GHz and mmWave bands)	to enable fast and soft V2I handovers - avoid beam training and time consuming target selection	CSI on sub-6 GHz, status information of vehicles	Kernel based ML (for positioning) and K-nearest neighbor (for HO decision)	RRU of sub-6GHz
[59]	Beam management in intelligent reflecting Surface (IRS) assisted single-cell mmWave	to mitigate the initial access and frequent handover challenges of conventional BM in presence of IRS	User mobility information and optimal IRS	DNN for environmental/mobility awareness phases	UE and BS
[60]	Multiple vehicle-multiple RSU association under high mobility	to max avg. rate vehicle while ensuring a target min. data rate with low signalling overhead	Observed channel information, experienced rates and violation probability of threshold rate	Actor critic based DRL for offline/online phases	mmWave RSU

of various types of obstacles can impact on the mapping of SNR values to the exact locations, the data to be utilized for training is generated by a network simulator. Then, by using the collected data, their ML algorithm learns the handover policy during offline learning phases and then select the best BS to maintain longer connectivity along the UE's trajectory. In this study, a real urban environment where multiple mmWave SCs are overlapped is considered. By using the double deep RL approach, it is shown that the proposed HO policy achieves outstanding performance on reducing the number of HOs by 20%-69% compared to the rate-based HO scheme. In [52], blockage prediction based HO scheme is studied by adopting ML. In the proposed solution, the BSs learn to predict that a certain link will experience blockage in the next few frames by using their observations of adopted beamforming vectors. By predicting blockage and the hand-off necessity, the serving BS is capable of proactively handover the UE to another BS with highly probable LOS link. Especially, in the scenario of single UE with two BSs, it shows that the proposed approach successfully predicts blockage/hand-off in close to 95% of the times, resulting to reduction of session disconnection for high reliability and low latency. The authors in [53] propose a ML-based beam management scheme to mitigate such disconnection time caused by beam misalignment. In their approach, various information collected from UEs such as location, mobility vectors, received SNR from BSs, and the current beam index are utilized to describe UE's context. As shown in Fig. 9, the 5G gNB predicts beam misalignment condition from collected UE's context information and initiates beam hand-off prior to disconnection. In the scenario of single UE and single gNB, the proposed algorithm achieves up to 98% accuracy in prediction and improved average throughput by 255% compared to the non-RL scheme in high mobility environments (36-108 km/h).

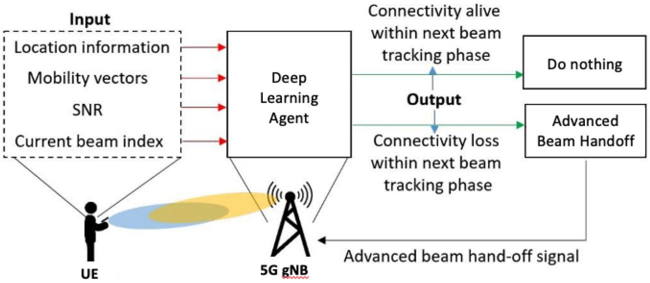

FIGURE 9. A proactive beam hand-off scheme proposed in [53].

While *beam training overhead* is one of challenges to use mmWave bands, ML-based approaches to mitigate such overhead are studied in literature. In [54], for the scenario of multiple distributed BSs for one UE, the perspective of training/coordination overhead is considered. When multiple BSs serve one UE at the same time, the coordination overhead would increase significantly for highly mobile applications in large-array mmWave systems. By using the uplink pilot signals received at multiple BSs, the proposed two-phase coordinated beamforming scheme in [54] tries to learn the correlation between the UE location and the beamforming direction in the first phase. Then, in the second phase, it relies on the developed deep learning model and predicts the optimal beamforming vector to enhance the coverage and latency with negligible training overhead. With the simulation results, the proposed method is shown to approach the achievable data rate of the algorithm using the optimal beamforming vectors with no training overhead. In [55]–[58], the partial similarities feature between low-frequency channel (sub-6GHz) and mmWave channels [69], [70] are exploited in order to reduce the beam training overhead in mmWave channels. When low-frequency CSI is utilized, due to small number of antennas in low-frequency band, inaccuracy can be an issue in estimating spatial feature of mmWave band. In [55], such estimation inaccuracy is managed by the convolutional neural network (CNN) based approach and the optimal beam in mmWave band could be predicted from low-frequency channel state information (CSI) (of pilot signals). The urban micro-cell scenarios having a 2 GHz link and 28 GHz link and UEs randomly distributed in a 120 degree sector are considered. Then, by simulations, it is demonstrated that the proposed scheme can successfully predict the optimal beam direction with over 94% accuracy in LoS scenarios, resulting in significant reduction of beam training overhead. Similarly, in [56], CSI of sub-6GHz bands is exploited for its ML-based approach in terms of power-delay profiles (PDPs). While beam management can be categorised as initial beam establishment and beam tracking, this paper focuses on the former one. The simulation results confirms that the proposed deep learning based beam selection can reduce the beam sweeping overhead by up to 79.3% compared to the conventional beam selection in 5G NR. The authors in [57] use sub-6GHz CSI to predict blockage status as well as the optimal mmWave beam. With the deep learning based approach, the mapping between a sub-6GHz channel to the optimal mmWave beam and blockage status is learnt. By the simulation, the proposed solution is shown to predict the mmWave blockages with more than 90% accuracy and select the optimal mmWave beams to approach no beam training overhead. The CSI of sub-6GHz channels is also used to predict the vehicle location by a ML-based approach proposed in [58]. By knowing vehicles' position, target mmW-RRUs can be prepared in advance. To speed up target selection and addition, K-nearest ML based handover predictions are carried out by utilising relationship between historical data of vehicle state information and handover performance. Moreover, due to coverage blindness in directional beams in mmWave bands, the work also proposes V2V-assisted target mmW-RRU preparation to enable soft V2I handovers by forwarding data over other vehicles which are actively served by the target mmW-RRU. This study specifically focuses on illustrating the feasibility of ML algorithms to assist handovers in mmWave vehicular networks, rather than performance improvement for ML algorithms.

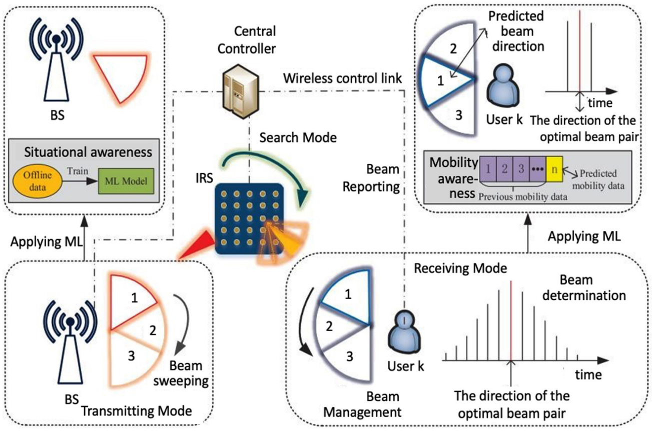

FIGURE 10. **The beam-space searching beam management [59].**

Intelligent reflecting surface (*IRS*) has attracted great attention recently to overcome blockage issue in mmWave networks. When direct link is not feasible between UE and mmWave BS, IRS systems are capable of reflecting signals to the desired direction by phase shifters. However, it poses a challenge for the beam management which is coordination of BS-IRS to jointly manage two-hop transmission. In this regard, the work in [59] proposes a ML-based IRS-assisted beam management for mmWave networks. To find the optimal IRS, situational and mobility aware learning phases are developed as shown in Fig. 10. In the situational awareness phase, the learning model at BS is trained with fingerprint dataset including user location and matched IRS. Therefore, for a given user location, the optimal IRS can be found. In the mobility awareness phase, an online ML approach employed at UE predicts next mobility information based on historical data. By integrating situational and mobility awareness phases, optimal IRS could be predicted beforehand to enable fast beam switching among IRSs. For performance evaluation of the proposed approach, the scenario of four IRSs deployed to serve the areas not covered by the single BS is considered. Based on the simulation results, the proposed solution is shown to reduce the system overhead of initial access significantly. For the case of 100 UEs, while the exhaustive search based algorithm produces the system overhead of 3.1 sec, the overhead occurred by the proposed solution is shown negligible. In addition, for high-dynamic scenarios, the proposed scheme achieves higher spectral efficiency (almost reaching near the optimum) than the conventional scheme by using predicted location of UEs.

In [60], the distributed ML framework is exploited to address computational complexity incurred by UE-BS association optimisation in a mmWave network scenario including multiple vehicles and multiple RSUs. The proposed distributed ML scheme considers two-phases learning, offline and online learning. In the offline phase, each RSU is modelled as an independent learning agent which is trained offline to avoid the online training complexity. While the learning agent at RSU explores different policies, the association of vehicle with RSU is performed and RSU's action is collected by a central entity, reward aggregator. Then, it computes the global reward based on the action of all RSUs and sends the accumulated global reward to RSUs. In the online learning phase, association of each vehicle can be decided with a single RSU or with multiple RSUs, which depends upon the individually learned policy during the offline training. The proposed framework aims to maximize the total data rate while ensuring minimum target data rate for all vehicles with low signalling overhead. In the urban macro network scenario including 6 RSUs and 8 vehicular UEs, the simulation results indicate that the proposed scheme achieves improved sum rate up to 15% and reduced rate outage by 20% compared to multiple baseline approaches.

VII. CONCLUSION

Thanks to the support for ultra low latency and highly reliable communications, the emerging 5th Generation mobile networks are expected to play an important role in providing services to a variety of V2X applications. However, as future networks continue to evolve, particular the introduction of new architectures and technologies to meet the capacity and latency requirements such as dense small cells and millimeter wave frequency bands, mobility management, especially for highly mobile V2X node become a challenge that must be addressed.

To this end, the focus of 3GPP has been concentrated on avoiding long delay introduced frequent legacy handovers and achieving zero mobility interruption so that users can be supported with uninterrupted connectivity. Even though the zero mobility interruption is made possible theoretically with DAPS, mobility interruption is still observed due to mobility related link failures. Therefore, a continuing research effort is required to overcome existing shortcomings and achieve the goal of zero mobility interruption.

From the existing works, we observed three main research directions in an effort to improve mobility. This first direction focused on handover decision making by reducing handover cost. In this regard, attempts were mainly based on selecting suitable BS which can offer longer connectivity without the need for beam (re)selection as well as utilising the caching capability of the mmWave cell for inter-BS handover reduction. In the second research direction, the works focused on enhancing the handover decision based on various dynamics of the user mobility and cell specific features for BS selection. The key idea was to identify factors that could influence the handover performance, and incorporated those factors in the process of handover decision making. The third research direction attempted to enhance beam management for better beam selection and alignment to ensure a robust link could be established. The works mainly focused on trading-off the directivity gain and beamwidth selection considering impact on handover and beam misalignment. For a common triggering event for both beam switching and handovers, enhancement on beam based measurement reporting was also attempted.

Additionally, modern techniques, particularly ML algorithms, have been explored and utilised as a promising tool in V2X networks for adaptive data-drive decision in beam based mobility management. Utilising the capability of ML for beam training, better mobility and blockage prediction can improve the accuracy of the beam/HO decision and avoid extra delay due to decision process involved in beam determination and BS selection. Considering limited computing facilities and the stringent latency requirements in V2X networks, some approaches such as learning model reduction or compression would be required. In addition, data are naturally generated across different units like vehicles and RSUs. Considering increase of overhead for coordination and sharing of information among various entities, distributed learning methods are highly desired. These will level up the future of V2X mobility with the utilisation of the integrated and advanced sensing and communication capability through distributed learning algorithms.

As new technologies constantly emerge to improve the future generation networks, some existing techniques in mobility management may become under-performing which directly challenge the overall network performance. Research interests in mobility management will be renewed to seek for improved solutions or novel solutions to integrate with the emerging technologies. We have already witness such an event with the emerging of IRS technology which has recently attracted great attention as a solution to overcome blockages in mmWave networks for future generation such as 6G [71]. The use of IRS immediately challenge the beam based mobility management by creating more complex multi-cell multi-IRS scenario where multi-point beam switching will become a major problem and require new techniques and analytical approaches to maintain connectivity across the various network attachment points.

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