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Uplink Reference Signals for Power-Efficient Handover in Cellular Networks With Mobile Relays

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ABSTRACT When a vehicle moves from one base station (BS) to another, a large number of on-board user equipments (UE) may simultaneously and individually perform a handover (HO) procedure, resulting in increased HO overheads. A mobile relay node (MRN), connected via a wireless backhaul to a donor base station (DBS), is deployed on the rooftop of a bus to improve the link quality and reduce the associated HO overhead via group mobility. However, at moderate to high speeds, the on-board UEs can still suffer from frequent HOs due to the MRN failing to HO to a new DBS using the legacy downlink measurement-based HO (DL-HO) method. As a consequence, the connection towards all associated mobile users will be lost which poses tight reliability requirements on the backhaul link to avoid becoming a single point of failure (SPoF). In order to improve the reliability during group handover, in this work, we propose an uplink reference signal (UL RS) based HO procedure (coined as UL-HO) for the MRN which relies on the existing sounding reference signal in long term evolution (LTE) /new radio (NR). In the proposed scheme, and unlike the legacy DL-HO procedure in LTE/NR, the measurement report (MeasReport) transmission is not required between MRN and the DBS, therefore the HO delay can be reduced, decreasing the SPoF chances and thus, uninterrupted services can be provided to on-board UEs. We investigate the gain in terms of HO rate, HO failure rate, ping-pong rate and power consumption (both at the UE and the BS). Performance evaluations demonstrate that the proposed UL-HO scheme outperforms the legacy DL-HO scheme in current cellular networks.

INDEX TERMS Uplink reference signal, sounding reference signal, handover, 3GPP cellular networks (LTE/NR), mobile relay node, simulation, power consumption, performance evaluation.

I. INTRODUCTION

To meet the needs of high-speed wireless connections, long term evolution (LTE) employs smart antenna techniques, adaptive coding, fast channel-dependent scheduling and modulation, etc., to offer a high peak data rate in ideal conditions. Still, the capacity of the LTE network is not equally distributed, i.e., the cell centre users have much higher throughput than cell edge users. As per the 3rd generation partnership project (3GPP), the successor of LTE is new radio (NR), aiming at further improving the cell edge user experiences and the system capacity. The future cellular network envisioned by mobile operators (see Fig. 1) may consist of a broad variety of deployment topologies including, but not limited to, macro base stations (BS[1]) vehicular networks, femtocells, small cells, fixed relay nodes (RNs), mobile RNs (MRNs), and device-to-device (D2D) connections. The rapid development of high-speed public transportation and infrastructures (e.g. bus, metros and trains) attracts travellers and favours the consumption of high data-rate demanding services on

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[1]In this paper, unless otherwise stated, we will use the term BS to indistinctively refer to an LTE Evolved Node B (eNB) or to an NR next-generation Node B (gNB).

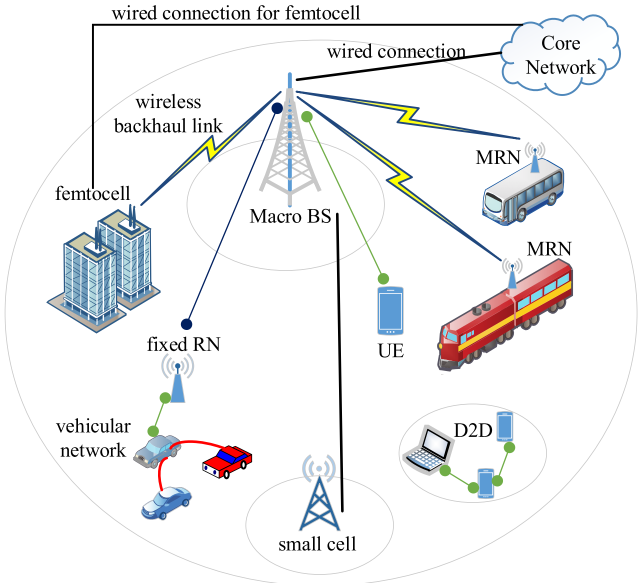

FIGURE 1. Illustration of multi-tier, complex, and dense future cellular network.

the move [1]. In complex deployments scenarios, as those described in Fig.1, data and voice communications on high-speed vehicles suffer high call-drop rate, bad channel condition, high UE power consumption and excessive signalling.

Increasing demand for voice and data services in public transportation has entailed new dimensions to the development and adaptation of mobile small cells (MSCs) in these highly dynamic scenarios. MSCs are enabled by low power access nodes that provide solutions to the capacity and coverage problems encountered in the fixed cellular networks i.e. without MSCs. The introduction of denser networks via MSCs deployments has a great impact on the handover (HO) process, for fast-moving users in general, and in particular for those UEs on-board vehicles, as the HO rate increases with speed. Group HO implemented by means of MSCs is arguably the most feasible solution to handle a large number of HOs associated with on-board UEs.

As shown in Fig. 1, in order to extend the coverage for fast-moving passengers and guarantee good on-board user experiences, the concept of MRN was introduced in 3GPP LTE Release 12 (R12) [2] along with the associated core and radio network technologies as listed by abbreviations in Table 1. The MRNs, sometimes called moving networks, have proven to effectively meet the dynamic user demands under stringent throughput and reliability demands [3]. Implementation of MSCs via MRNs can be integrated within public transportation vehicles to serve its on-board UEs. For high-speed public transportation, MRNs play a major role allowing mobile UEs to maintain network connectivity with good quality of experience (QoE) to the macro BSs. MRNs can be roof-mounted on vehicles whereby the on-board passengers can connect to the network through the MRN via a so-called donor base stations (DBSs) [2]. Among other advantages, MRNs can provide the coverage and capacity of the network comparable to the pico and femto BS while at the same time reducing the deployment cost. In addition, easier site selection and lower equipment cost motivate the vendors, service providers and academic researchers to focus on enhanced solutions for the implementation of MRNs. In densely deployed urban scenarios, link availabilities are usually dependent on interference rather than on coverage. Due to the low transmit power of MRNs, lower interference is generated towards the UEs outside the vehicle. Hence, deploying dedicated MRNs on public transportation vehicles seems very promising for improving the quality-of-service in future mobile communication systems.

TABLE 1. List of abbreviations.

Abbreviation	Explanation
3GPP	3rd generation partnership project
AMF	access and mobility management function
BBU	baseband unit
BS	base station
D2D	device to device
DBS	donor base station
DL-HO	downlink handover
DL RS	downlink reference signal
DoA	direction of arrival
FDD	frequency-division duplex
HO	handover
HOcmd	handover command
HOconf	handover confirm
HOF	handover failure
LTE	long term evolution
MeasReport	measurement report
MME	mobility management entity
MRN	mobile relay node
MSC	mobile small cell
NR	new radio
OPEX	operational expenditure
OFDMA	orthogonal frequency-division multiple access
PP	ping-pong
QoE	quality of experience
RACH	random access channel
RAT	radio access technology
RB	resource block
RE	resource element
RLC	radio link control
RLF	radio link failure
RN	relay node
RRC	radio resource control
RSRP	reference signal received power
s-DBS	serving donor base station
SGW	serving gateway
SPoF	single point of failure
SRS	sounding reference signal
TB	transport block
t-DBS	target donor base station
ToA	time of arrival
TTT	time-to-trigger
TU	typical urban
UE	user equipment
UDG	user data gateway
UL-HO	uplink handover
UL RS	uplink reference signal
UNs	user nodes
UPF	user plane function

A MRN mounted on the rooftop of a vehicle is capable of performing group HO on behalf of its on-board UEs. In this setup, instead of having all the on-board UEs performing the HO procedure individually, only the MRN will perform the HO between some source and target DBS. The MRNs can significantly reduce the signalling overheads both on the network and the radio interface along with the HO latency by providing a seamless HO experience for on-board UEs as compared to fixed relays [4]. A MRN requires the HO process to at least maintain its active connection to any given DBS and avoid the termination or interruption of a current service as much as possible. However, at high speed, the MRN can still suffer from frequent HOs, i.e. when a MRN fails to HO to a new DBS. In this case, the connection of all associated mobile users will be temporarily lost. Hence, the main issue is to guarantee the reliability of the backhaul link which may become a single point of failure (SPoF). Therefore, noting that the introduction of MRNs can still deteriorate the HO performance, in this work, a HO solution is proposed to reduce the MRN SPoF. This solution, unlike the legacy MRN HO scheme in LTE and NR, relies on UL-based measurements for triggering the HO procedure, and it is described in the next subsection.

A. PROBLEM STATEMENT AND MAIN CONTRIBUTION

In this work, we focus on reducing the MRN HO signalling overheads in order to minimize the power consumption due to the HO procedure. In addition, we address the problem of MRN HO failure (HOF) to a DBS.

In current cellular networks (i.e. LTE and NR), the UE/MRN performs downlink reference signal (DL RS) measurements and, upon identifying a better neighbouring cell, the UE/MRN sends a measurement report (MeasReport) to the serving BS/DBS. In [23], we found that the measurement of DL RSs constitutes a high power consuming task. In addition, the MeasReport transmissions constitute a 37% of the total HO signalling, therefore being a major contributor to power consumption.

In this work, we propose an uplink HO (UL-HO) scheme to cope with the aforementioned problems of legacy downlink HO (DL-HO) procedure. Using this method, these problems can be solved by transmitting the UL RS from the MRN side and letting the neighbouring DBSs measure UL RS instead of relying on the MRN measuring and reporting DL RS, as in traditional cellular mobility [6]. This way, the network can track and locate the MRN using UL RS based measurements [6]. These measurements are processed in a centralized network entity to decide which DBS will serve the MRN. Using the proposed method, MeasReports between the MRN and the network are not required, thus the HO delay can be reduced, minimizing the chances of SPoF, reducing the HO related signalling messages as well as power consumption. The UL-HO scheme is a step forward to reduce energy consumption that has a direct impact on CO_2 emissions and operational expenditure (OPEX) of the operator.

B. RELATED WORK

3GPP LTE-A Release-10 has introduced the support for fixed cellular relays to extend the cell coverage and improve the spectral efficiency by reducing the so-called user-to-infrastructure distance. The 3GPP study items TS36.416 of Release 11 [7] and TS 36.836 of Release 12 [2] address the deployment of MRNs mounted on top of a high-speed train. In addition to MRNs, three other deployment alternatives were examined and evaluated in [2], [7]. First is the dedicated deployment of macro eNBs to cover the railway track with directive antennas and overlapping coverage. The second solution is the dedicated placement of macro eNBs with L1 repeaters that can amplify and forward the signal in a specific frequency band. L1 repeaters deployed in the train can reduce the penetration loss and UE transmit power but SINR cannot be improved as it also amplifies the noise with the desired signal. The last solution is through using LTE as backhaul and WiFi as access on-board, which is less complex (requires no change to specifications) and low-cost solution in comparison to the deployment of MRNs. The wireless node (WiFi access point) in the train connects as an LTE user to the eNB and all UEs on-board can use this node [2]. The challenges of providing cellular services to on-board passengers using dedicated macro eNBs with larger cell overlap include high Doppler shift, high penetration loss, high HOFs, serious signalling congestion, high UE power consumption and low spectral efficiency. In this work, we adopt the deployment of MRNs, as opposed to other presented alternatives, owing to its suitability as described hereafter. For example, a MRN provides a reduction in HOFs and signalling overheads using group HO procedure. It has low cost over other solutions requiring dedicated BSs, and improved quality of service. In addition, the advanced signal processing in relays reduces the Doppler shift. Furthermore, reduction in penetration loss and high user battery lifetime by reducing the UE transmit power are its key features. In [7], a similar study is conducted to improve the coverage in high-speed train scenario with MRNs. The study was based on a speed of 300 km/h, known path, high penetration loss through carriage walls and pedestrian speed of on-board UEs relative to MRN. A straight line track of the train was considered in the presence of normal macro users as well. The MRN serving DBS link was found using path loss. The on-board active users were served by the MRN [7]. In comparison to this work, our solution presents further benefits as it shows the benefits of group mobility, reduces the signalling overheads and the power consumption during MRN HO to DBS.

A HO procedure considering a MRN mounted in a train for LTE-A network described using a mathematical model is presented in [8] to compare the signalling cost between 3G and 4G networks. Therein, it is found that, by using MRNs in the LTE-A network, the HO delay, HO cost and drop calls can be reduced. This work is relevant as it shows the benefits of using MRNs in terms of group mobility and signalling cost. Similarly, the benefit of deploying a MRN has been discussed in [9]. The results show that when the vehicular penetration loss is moderate to high, the MRN can notably lower the end-to-end outage probability. Also, the outage probability performance of a MRN in the presence of co-channel interference has been studied in [10] considering the effect of small scale fading and path loss. The work in [11] used a different method to solve high HO signalling overhead issue in 5G rail networks. A MRN based fixed-trajectory group pre-HO authentication mechanism proposed in [11] performs the HO authentication procedure in advance in order to provide uninterrupted services for the UEs on-board.

A user-transparent mobility concept is proposed in [6]. This method is based on the transmission of UL RS using Zadoff-Chu signature sequences for reliable detection at the BS. The suitability of UL beacon resources and reliability of the proposed scheme reveals its advantages over legacy DL-HO mechanisms. The idea of utilizing UL RS for joint tracking of a group of users is proposed in [12]. The users moving together are grouped into clusters and each group is tracked by a single UL RS. The reduction of the required UL RS resources allows the RS to be transmitted more frequently and reduces the interference. The UL RS concept can also be extended for accurate device location and user tracking. An UL RS based accurate device positioning and tracking algorithm for the 5G ultra-dense network is proposed in [13]. In this technique, UL RS are exploited for efficient joint estimation and tracking of the direction of arrival (DoA) and time of arrival (ToA) of the user nodes (UNs). In comparison to works in [6], [12], [13], our proposed UL-HO has unique features, i.e. the use of sounding reference signal (SRS) as an UL RS, and applicability to MRN deployments. An UL RS based mobility management procedure proposed in [14] show that this method can save UE power consumption by up to 63% in comparison to the DL mobility method. Therefore, work in [14] suggests that some potential UE power consumption savings could be also achieved using UL-HO scheme as considered in our paper. Similarly, in [15], the results show that the UL-HO method outperforms over DL-HO for both ''Rural with high-speed UEs'' and ''high-speed train'' scenarios in terms of lowest UE power consumption. According to [16], the UL mobility scheme can reduce the HOF rate and the UE power consumption in NR. Noteworthy, in [14]–[16], the authors seem to address the UE power consumption only, whereas herein we provide both UE and BS power consumption analysis. Also, these works have not mentioned the applicability of UL-HO for the MRNs.

C. SCOPE AND MAIN OBJECTIVES

In this paper, we address the HO performance of 3GPP cellular networks (i.e. LTE/NR) in the presence of a MRN and the associated power consumption in a scenario where a cluster of UEs is traveling on a bus along a fixed-trajectory. The UEs on-board the bus are serviced from the MRN and the MRN is connected to a DBS via a wireless backhaul. The remaining out-board users are connected directly to macro BSs. We provide a solution to the problem of MRN HOF to a DBS, to reduce the SPoF cases and provide uninterrupted services for UEs on-board.

Unlike in existing literature, we propose the use of the SRS to act as UL RS in our handover scheme. This would require a minimum alteration of the standards since SRS is already used in both LTE and NR. Our UL-HO procedure is radio access technology (RAT)-agnostic and future proof in comparison to the legacy DL-HO scheme in LTE and NR because it reduces the HO signalling overheads and the power consumption. In fact, the legacy LTE and NR DL-HO procedures follow the same principles, with only minor nomenclature differences [17], [18]. For the results section, however, we will assume LTE as a reference scenario. We extend the UL-HO for the case of MRN deployments. Using this technique, no MeasReport transmission/reception is required between MRN and the DBS, and thus the HO delay can be reduced, reducing the chances of HOF for the MRN. Herein, we investigate the improvements bought by the proposed UL-HO for both scenarios, with/without deploying MRN in terms of reduction in HO rate, HOF rate, ping-pong (PP rate), along with both UE and BS power consumption, the latter not being considered in existing works. We believe this study contributes to determining the potential benefits (i.e. uninterrupted services to on-board UEs) of using MRN together with the UL-HO procedure. It should be noted that the performance of the MRN HO while taking into account the power consumption of the air-interface signalling, the UL-HO using SRS and UL-HO with MRN is largely overlooked in the literature.

The rest of the paper is organized as follows: Section II describes an overview of the UL-HO procedure involving MRNs. Section III discusses the simulator modelling aspects. In Section IV, simulation results are presented, and finally, Section V provides some concluding remarks along with future research directions.

II. UPLINK HANDOVER (UL-HO) PROCEDURE FOR MOBILE RELAYS

As mentioned earlier, a MRN is a BS/access point mounted on the vehicle and connected wirelessly to a DBS via the Un radio interface to provide indoor wireless connectivity to the end-users. The UEs are connected to the MRN via the Uu interface. The MRN supports both BS as well as a subset of UE functionalities to connect to the DBS. Four different mobile relay architecture alternatives (namely Alt.1 to Alt.4) have been discussed in 3GPP [2]. The MRN inter-DBS mobility procedure under architecture Alt.1 is identical to UE inter-eNB mobility in LTE [17] and UE inter-gNB mobility in NR [18]. A MRN has additional requirements, including persistent IP connectivity during HO and group mobility, so, relay architecture Alt 1 is deemed more appropriate [19]. The Alt. 1 relay architecture is shown in Fig. 2 where the user interface (i.e. S1-U interface in LTE) is between the RN and user data gateway (UDG) of the UE. The MRN HO reuses existing UE HO procedures with some enhancement if needed. Also, the HO procedure in the architecture Alt 1 is more simplified and its latency analysis demonstrates better performance [19], which justifies our selection.

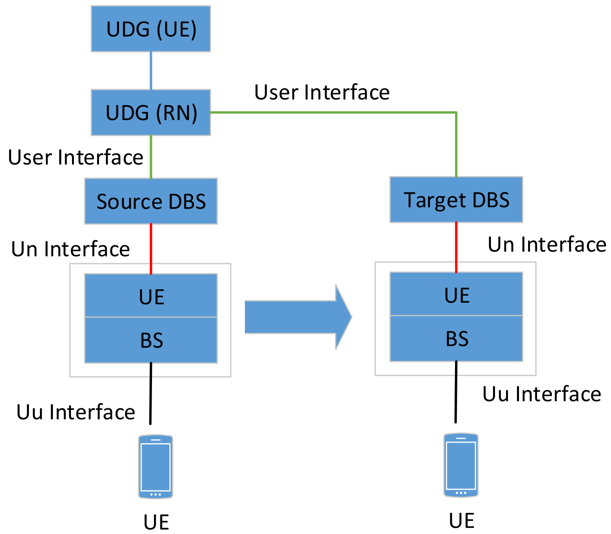

FIGURE 2. Alt 1 relay architecture (adapted from [2]).

A. UE HANDOVER

In the presence of a MRN, the measurement phase can be divided into two phases: UE measurement, and MRN measurement. For DL-HO, we assume that the on-board UEs will not perform DL RS measurements from neighbouring BSs as the MRN will perform the measurements from DBSs on their behalf. Similarly, for UL-HO, the on-board UEs will not transmit UL RSs to nearby BSs, only the MRN will do this on their behalf. In case of MRN HOF to a DBS, the on-board UEs will perform their individual HO procedure with the nearby BSs. The out-board UEs are directly connected to BSs through their individual HO procedure for both UL-HO and DL-HO cases. The DL-HO and UL-HO procedure for an individual UE is described in our recent work [23]. In short, an individual UE HO is needed for all out-board UEs and for on-board UEs only in case of a MRN HOF to DBSs.

B. MRO HANDOVER

The architecture Alt 1 MRN DL-HO procedure is shown in Fig. 3 (a) for current cellular networks [2], [6]. As per the standardized technical specification, [17], [18], 3GPP is still relying on the DL measurement-based HO procedure for both LTE and NR (identical in both RATs except for some entity renaming). Hereafter, we will adopt a generic naming convention as a way to indistinctively refer to both LTE and NR use cases. For example, the centralized entity in Fig. 3 could be implemented in the mobility management entity (MME) in LTE or the access and mobility management function (AMF) in NR. Similarly, the user data gateway (UDG) in Fig. 3 could be the serving gateway (SGW) in LTE or the user plane function (UPF) in NR. Finally, in our proposed HO scheme, we will use the term BS referring to either an LTE eNB or an NR gNB. In the DL-HO scheme, Fig. 3 (a), the network sends the DL RS which is received at MRN, allowing the MRN to perform DL signal strength measurements. The MRN processes these measurements and sends a MeasReport back

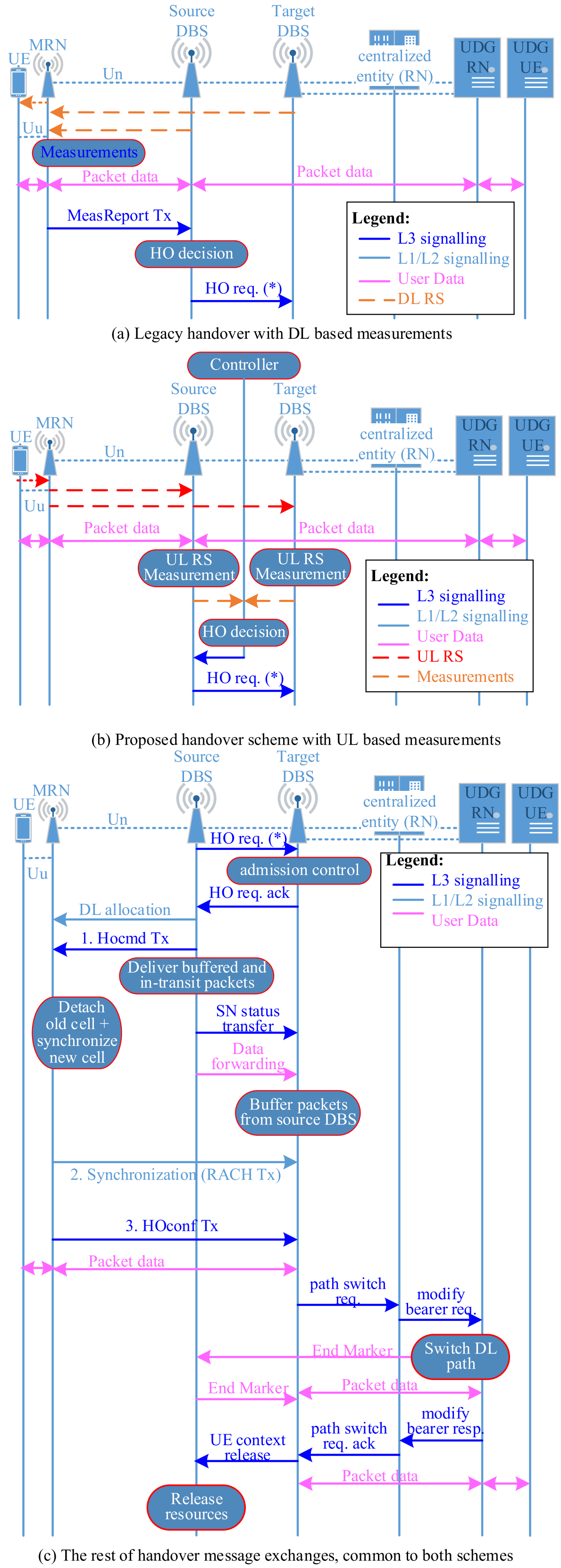

FIGURE 3. Architecture Alt 1 MRN HO procedure(a) legacy handover with DL based measurements (b) proposed handover scheme with UL based measurements (c) the rest of handover message exchanges, common to both schemes (adapted from [2], [6], [17], [18].

to the source DBS (s-DBS). Based on the MeasReport, the s-DBS takes the HO decision and sends a HO request to the target DBS.

On the contrary, using the UL-HO technique shown in Fig. 3 (b), the MRN sends UL RSs which are received at several neighbouring DBSs, allowing the network to perform UL signal strength measurements. Both the s-DBS and potential target DBSs (t-DBSs) perform signal strength measurements over the set of time-frequency resources carrying the UL RS sent by the MRN. Subsequently, each DBS computes the UL RS received power (UL-RSRP) that is sent to the controller. The s-DBS and t-DBSs can be connected to a central network controller via existing interfaces (such as e.g. X2 or S1 in LTE). These measurements are processed in the controller to decide which DBS shall serve a given MRN. Using this method, no MeasReport is required to be transmitted from the MRN in comparison to the legacy DL-HO procedure (see Fig. 3 (a) vs Fig. 3 (b)), thus it reduces the power consumption, and OPEX. It is to be noted that the RSs occupy pre-defined resource elements (REs) on the orthogonal frequency- division multiple access (OFDMA) resource grid to support UL and DL transmission. RSs only facilitate transmission of user data and do not carry any user data.

Among the existing RS in LTE and NR, the SRS is a RS transmitted by the UE/MRN in the UL direction that is used by the BS/DBS to estimate the quality of the UL channel. The channel is typically estimated for large bandwidths outside the span assigned to a UE/MRN [5]. Our solution utilizes UL RS for handover and, in particular for LTE and NR one could use for example SRS (which is one type of RS, but not the only one). The benefits of using the UL-HO scheme come at the cost of some new requirements. The first requirement is the time synchronization between DBSs as several DBSs need to receive the UL RS simultaneously. Secondly, the existing interfaces (e.g. X2 or S1 in LTE) require some minor standard upgrades in defining the information elements to be communicated between the DBSs/BSs and controller. Lastly, there is a need to coordinate UL RS resources between different cells to avoid pilot contamination, i.e. having different MRNs sending UL RS over the same resources thus inducing erroneous measurements.

As per Fig. 3 (b), the controller measurement phase starts with the processing of the UL-RSRP measurements (e.g. time-averaging). If an "entry condition" is fulfilled, the controller triggers the HO decision and sends the candidate's t-DBS information to the s-DBS. Analogously to the A3 event in LTE and NR HO [21], we define an equivalent "UL A3 event" to be used as entry condition to assess if the UL-RSRP of the t-DBS is stronger than the UL-RSRP of the s-DBS plus a hysteresis margin (herein called UL-offset). The entry condition has to be valid during a specified time defined by the UL time-to-trigger (UL-TTT) parameter. Upon successful reception of the candidate's t-DBS information at the s-DBS, a HO request is issued from the s-DBS to the t-DBS. The rest of the HO procedure is common to both DL-HO and UL-HO schemes as shown in Fig. 3 (c). Upon receiving the HO request, the t-DBS then decides whether or not it can admit the MRN and feedbacks this information to the s-DBS. Upon successful admission, the s-DBS transmits the HO command (HOcmd) to the MRN with the necessary information to synchronize and perform initial access to the t-DBS. Upon successful reception of the HOcmd, the MRN accesses the t-DBS, by means of a random access (RA) procedure via the RA channel (RACH). With successful RA completion, the t-DBS receives a HO confirmation (HOconf) message from the MRN. Finally, the s-DBS receives a HO complete message from the t-DBS that informs about the success of the HO process. In the described context, HO optimization deals with the adjustment of the TTT, and the A3 offset to achieve a good compromise between HO frequency and HO reliability [28].

III. SYSTEM MODEL

A MATLAB based system level simulator is used considering a hexagonal grid deployment of 16 tri-sectored BSs with scenario wrap-around to allow fair interference conditions across the scenario. A set of 200 UEs is randomly placed over the scenario, with the assumption that the first twenty-four UEs (12%) are on-board a bus, moving at a fixed speed and a specified direction, and the remaining 88% out-board UEs follow rectilinear motion at a fixed speed with initial random directions uniformly distributed between [0°, 360°]. The out-board UEs are randomly placed outside the bus and all over the scenario. A roof-top mounted MRN is deployed on the bus to improve the link quality and reduce the associated HO overhead via group mobility. The users on-board are getting cellular services from the MRN and the MRN is connected to a DBS via a wireless backhaul. This wireless backhaul operates over the same bandwidth as the access link (i.e. in-band wireless backhaul is assumed). It is further considered that the bus is traveling along a road situated at the cell edge of the DBSs across the simulation scenario. We motivate this by noting that DBSs and MRN share the same access band and, therefore, MRN passing close to the DBS may cause excessive interference and reduce the MRN cell coverage area. In addition, the UEs will experience poor radio link conditions at the cell-edge, thus directly benefiting from this MRN deployment. The simulation scenario is presented in Fig. 4 and the simulation implementation is largely based on an LTE deployment. Given the similar nature of LTE and NR HO procedures, the expected evaluation in an NR simulator would comparatively provide similar outcomes. A thorough description of the simulator's features is covered in [23], [28], herein the main simulation assumptions are summarized in Table 2.

A. POWER CONSUMPTION MODEL

We are interested in the power consumption related to the HO signalling over the air interface in both UE/MRN and BS transmissions and receptions, namely: the MeasReport, the HOcmd, the RACH, and the HOconf transmission and

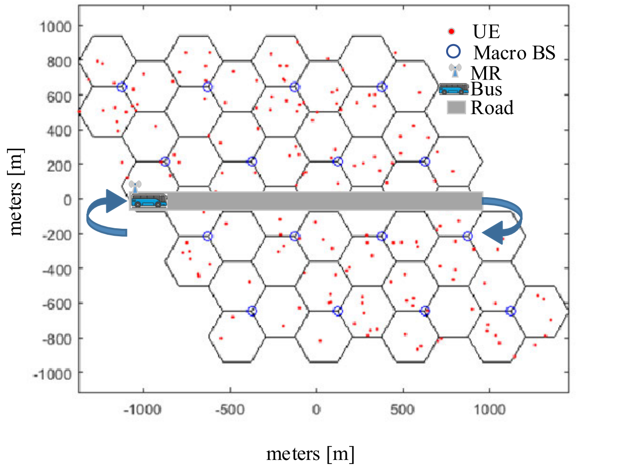

FIGURE 4. The considered simulation scenario, with the bus following a wrap-around trajectory over the specified road once it hits the rightmost border.

TABLE 2. Simulation parameters and assumptions.

Feature	Implementation
Network topology	A hexagonal grid of 16x3=48 cells (wrap-around included)
Inter-site distance	{500} m
System Bandwidth	B_{sys} =5 MHz (paired FDD), with $N_{RB}^{DL} = N_{RB}^{UL} =$ 25 RBs at carrier frequency f_c =2.1GHz, 1TB=6 RBs, $N_{TB}^{DL} = N_{TB}^{UL} = \lfloor 25/6 \rfloor$
BS power	43 dBm
UE and MRN Power	23 dBm
Antenna patterns	3D model specified in [19], Table A.2.1.1.2-2
Channel model	6 tap model, Typical Urban (TU)
Shadowing	Log-normal Shadowing Mean 0 dB, Standard deviation: 8dB
Propagation model	$L = 130.5 + 36.7 \log_{10}(R)$ R in km, between UE and BS $L = 140.7 + 36.7 \log_{10}(R)$ R in km, between MRN and DBS [19]
UE/MRN speed	from the set {30, 60, 90} km/h
RLF detection by L1 of UE	T310=1s, N310=1, N311=1 as specified in [21] Q_{in}=-4.8 dB; Q_{out}=-7.2 dB as specified in [22]
DL RS Periodicity	$T_{DLRS} = \{20, 40, 60, 80\}$ ms
HO parameters	DL TTT= $N_{samples} \times T_{DLRS}$, $N_{samples} = 3$ UL TTT= $N_{samples} \times T_{SRS}$, $N_{samples} = 3$ DL and UL A3 offset = {3} dB.
Number of TBs per signalling	$N_{TB}^{MR} = 1$ TB; $N_{TB}^{HOcnf} = 1$ TB; $N_{TB}^{HOcmd} = 2$ TBs; N_{TB}^{RA} =1 TB.
Power consumption parameters	$\eta = 0.311$ (31.1%), $P_{RF,BS} = 12.9$ W, $P_{RF,UE} =$ 2.35 W, $P'_{BB} = 29.4\,W$, $P_{TxBB} = 0.62\,mW$, $P_{RxBB} = 0.97. R_{Rx} + 8.16\,mW$
Signalling transmission times	T_{BS}^{HOcmd} = 1ms; T_{UE}^{MR} = 1ms; T_{UE}^{HOcnf} = 1ms; $T_{UE}^{RACHtx} = 1$ ms

reception. A detailed derivation of the mathematical model for the calculation of the power consumption is covered in our recent work [23]. Here, we only show the final equations to calculate both the transmitted and received power consumption. The parameters used to calculate the power consumption are presented in Table 2. The supplied power to the BS, necessary to either transmit (Tx) or receive (Rx) signalling s is denoted by $P_{BS,sup}^{s,Tx/Rx}$, and can be calculated as follows,

$$P_{BS,sup}^{s,Tx/Rx} = P_{BS,Tx/Rx}^{s} \Big/ \eta + N_{TB}^{s} \Big/ N_{TB}^{DL} .(P_{RF,BS} + P'_{BB}), \quad (1)$$

where $P_{BS,Tx/Rx}^{s}$ is the allocated BS transmitted or received power (in W) per signalling message s and η is the power amplifier efficiency. $P_{RF,BS}$ denotes the supply power contribution of the RF equipment, which is conveniently scaled by the portion of utilized resources by signalling message s. Similarly, P'_{BB} is the baseband unit (BBU) power consumption in watts (see Table 2). Equally, the supply power required for the UE to transmit or receive signalling message s, $P_{UE,sup}^{s,Tx/Rx}$, is given by,

$$P_{UE,sup}^{s,Tx/Rx} = P_{UE,Tx/Rx}^{s} + N_{TB}^{s} \Big/ N_{TB}^{UL} .(P_{RF,UE} + P_{Tx/RxBB}), \quad (2)$$

where $P_{UE,Tx/Rx}^{s}$ is the allocated UE transmitted or received power (in W) per signalling message s, and where the supply power contribution to the RF and BB part is also scaled by the portion of utilized resources by signalling s. $P_{Tx/RxBB}$ is the transmitted or received UE BBU power (see Table 2) where R_{Rx} is the received data rate that is a multiplication of signalling rate and the carried bits in a transport block (TB).

The time-averaged supply power to capture the time-domain system dynamics is given by,

$$\bar{P}_{x,sup}^{s,Tx/Rx} = P_{x,sup}^{s,Tx/Rx} \cdot T_x^s \cdot R_x^s, \quad (3)$$

where T_x^s is the signalling duration in seconds and R_x^s is the signalling rate which will be obtained from system-level simulations.

B. UPLINK REFERENCE SIGNAL IMPLEMENTATION

In this work, we will adopt the sounding reference signal (SRS), defined in 3GPP LTE/NR standards [24], [25], to implement the UL RS used during HO. In current implementations of LTE/NR, SRSs are utilized to estimate the UL channel. Thereby the BS can perform accurate link adaptation, maintain uplink synchronization, determine the channel quality information in the UL direction, and support frequency selective scheduling, among others. In addition, the SRS angle of arrival (AoA) or channel reciprocity property can also be used to beamform data transmission in the DL [27]. The BS configures the sounding periodicity, bandwidth, frequency, and subframe offset via higher-layer signalling on a cell-wide basis. Furthermore, each UE (or MRN in our case) is individually configured with different sounding periodicities, bandwidths, sequences, and hopping patterns in order to achieve resource orthogonality.

Table 3 provides the considered SRS parameters in this work. The SRS bandwidth configuration parameter ($\boldsymbol{C_{SRS}} \in \{\mathbf{0, 1, \ldots, 7}\}$) along with the SRS bandwidth parameter ($\boldsymbol{B_{SRS}} \in \{\mathbf{0, 1, 2, 3}\}$) jointly define the total bandwidth to be sounded (within the system bandwidth) along with the partial sounded bandwidth ($\boldsymbol{m_{SRS,b}}$, with $\boldsymbol{b} = \boldsymbol{B_{SRS}}$) at each SRS transmission. These values are tabulated and can be found

TABLE 3. SRS parameters and value.

Feature	Values
SRS periodicity (T_{SRS})	$T_{SRS} \in \{20, 40, 60, 80\}$ ms [26] Table 8.2-1.
Number of transmission combs (K_{TC})	K_{TC} =2 [24]
Number of SRS antenna ports (N_a)	N_a =1 (used for sounding)
OFDM symbols per SRS resource	N_{symb}^{SRS} = 1
Cyclic shift (n_{SRS}^{cs})	$n_{SRS}^{cs} \in \{0, 1, ..., 7\}$ [24]
Bandwidth Configuration (C_{SRS})	C_{SRS} =7 [25]
SRS Bandwidth (B_{SRS})	$B_{SRS} = b = 1$ ($m_{SRS,0}$ =12 RBs)
SRS hopping parameter (b_{hop})	b_{hop} = 0 (hopping over entire bandwidth) [24]
SRS configuration index (I_{SRS})	I_{SRS} = {0,1, 2, ... 636}, [26]

in [24] and [25] for LTE and NR respectively. Moreover, a hopping parameter ($b_{hop} \in \{0, 1, 2, 3\}$) further defines the frequency hopping pattern followed by different SRS transmissions in order to sound a portion or the entirety of the sounding bandwidth. For example, when $b_{hop} = B_{SRS}$ then frequency hopping is done over the entire sounding bandwidth. The above frequency-domain parameters define the cell-specific configuration common to all SRS transmissions in a cell. In addition, UE-specific parameters will be allocated to guarantee SRS resource orthogonality and are described hereafter. In the frequency domain, a given SRS transmission bandwidth will occupy the subcarriers defined by a comb parameter K_{TC}. For example, K_{TC}= 2 allows multiplexing SRS transmissions over the same bandwidth by assigning a comb index k_{TC}= {0, 1 for odd and even subcarriers. Also in the frequency domain, UE-specific frequency allocation parameter n_{RRC} [24] will determine the initial position (in RBs) for the SRS transmission of a given UE (or MRN in our case). Code-domain multiplexing provides an extra degree of orthogonality for SRS transmissions whereby Zadoff-Chu sequences are allocated to different UEs. In particular, the standard defines a cell-specific sequence identifier (n_{ID}^{SRS}) along with a UE-specific sequence cyclic shift index ($n_{SRS}^{cs} \in \{0, 1, \ldots 7\}$) in order to guarantee orthogonality in the code domain. In the time domain, the SRS in LTE occupies the last OFDM symbol in a subframe of 1ms. Then, it is possible to configure SRS transmissions with SRS periodicities (T_{SRS}) ranging from 2ms to 320 ms [26].

The UE-specific parameter assigning this periodicity is the SRS Configuration Index ($I_{SRS} \in \{0, 1, ..636\}$) yielding into different SRS periodicities as described in [26]. Similarly, we assign DL RS periodicities (T_{DLRS}) in case of DL-HO as shown in Table 2. In this work, we will simulate different SRS periodicities (T_{SRS}) and DL RS periodicities (T_{DLRS}) to determine the impact on power consumption and to find an optimum SRS periodicity value for various case scenarios.

Fig. 5 illustrates most of the aforementioned SRS parameters for the case of two SRS transmissions. Moreover, the considered numerical values for the SRS parameters used in the system-level simulator are detailed in Table 3.

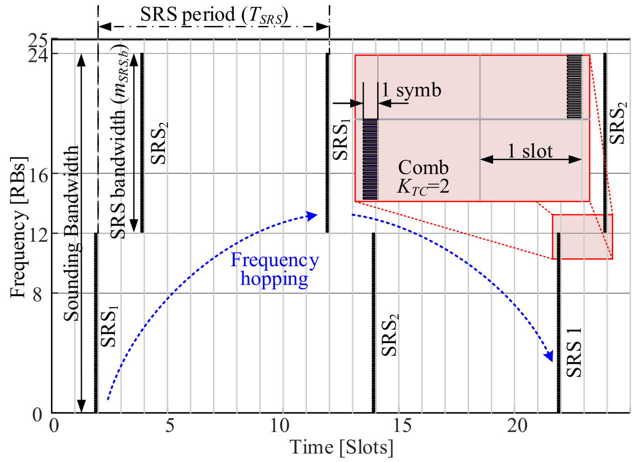

FIGURE 5. Example of two orthogonal SRS transmissions (SRS_1 and SRS_2 in the graph) along with main SRS design parameters.

IV. SIMULATION RESULTS

In this section, we provide a simulation evaluation of the HO performance and its related power consumption, with and without deploying a MRN. Both the DL-HO and UL-HO procedures are evaluated for comparison purposes. Mainly, the potential benefits of using a MRN with UL-HO procedure are shown, considering the HO performance metrics and power consumption. Out of 200 UEs deployed in our scenario, 24 UEs are traveling on the bus at a fixed-trajectory and the remaining out-board UEs are moving outside the bus, all over the scenario with fixed speed and random directions. Four case scenarios are simulated, namely, 'DL-HO w/o MRN', 'UL-HO w/o MRN', 'DL-HO w MRN' and 'UL-HO w MRN'. The cases without MRN deployment means that all on-board UEs will perform their individual HO procedure with the macro BS. However, the cases with MRN roof-mounted on the bus means that only the MRN will perform the HO procedure between different DBSs on the behalf of the UEs on-board. For the simulation evaluation, we assume DL-HO and UL-HO A3 event check occurs at each DL/UL RS periodicity to have a fair comparison, see Table 2 and Table 3 for details. For example, we assume that each UE/MRN will check the A3 event after a specified time defined by T_{SRS}/T_{DLRS}. Similarly, we assume that the number of samples of measurement updates to trigger the HO are N_{sample} = 3, the same number for both DL-HO and UL-HO case. Also, the TTT is $N_{samples} * T_{SRS}/T_{DLRS}$ and A3 offset is fixed to 3dB for both the DL-HO and UL-HO cases (see Table 2 for details). In the next subsections, we will show the performance of DL-HO and UL-HO without MRN in Section IV.A, with MRN in Section IV.B, and all four aforementioned cases of with/without MRN total power consumption in Section IV. C.

A. WITHOUT MOBILE RELAY NODE

In this section, we will present the simulation results for two cases of without MRN, namely, 'DL-HO w/o MRN' and 'UL-HO w/o MRN'. Three different speed values are simulated, {30, 60, 90} km/h, to find the benefits that

UL-HO brings in terms of improving HO metrics and power consumption as a function of speed.

1) HANDOVER METRICS

The impact of varying UE speed and DL/UL RS periodicities on the HO rate is shown in Fig. 6. The HO rate is measured as the total number of triggered HO events ($\boldsymbol{N_{HO,total}}$), including successful ($\boldsymbol{N_{HO,success}}$) and failed ($\boldsymbol{N_{HO,fail}}$) HOs, divided by the simulation time (i.e. $\boldsymbol{T_{sim}} = 60$ seconds in our case). Formally, the HO rate ($\boldsymbol{R_{HO}}$) can be expressed by:

$$R_{HO} = \frac{N_{HO,total}}{T_{sim}} = \frac{N_{HO,success} + N_{HO,fail}}{T_{sim}}. \tag{4}$$

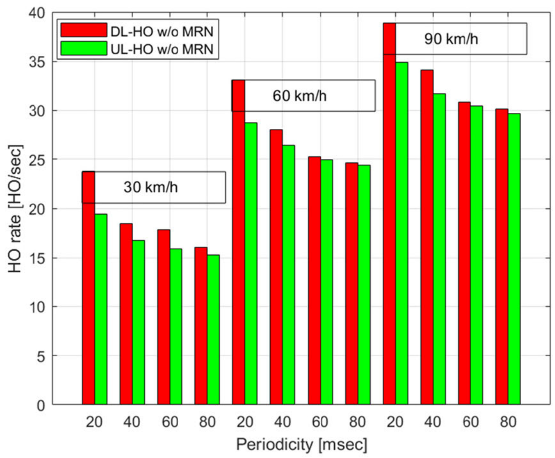

FIGURE 6. Impact of varying UE Speed and UL/DL RS periodicity on HO rate (without MRN).

The first observable trend in the graph shows that as the UE speed increases, the HO rate increases for both DL-HO and UL-HO schemes, which is expected. We argue that when speed increases, UEs spend less time in the "HO region" and move out of the s-BS before the HO procedure completes thus causing more HOFs (see Fig. 7) which consequently increases the HO rate. The second trend reveals that, in general, across all simulated speeds, utilizing the UL-HO procedure is beneficial in terms of reducing HO rate (i.e. the HO rate of UL-HO for all speeds and periodicity cases is lower in comparison to DL-HO). This is because of the fact that UL-HO eliminates the MeasReport signalling thus the HO procedure complete before the UE loses its connection with the s-BS. Thirdly, we are able to identify, by inspecting Fig. 6, that low periodicities (i.e. 20 ms) have a higher HO rate. This is because of the fact that too many updates in measurements cause many A3 event evaluations consequently leading to unnecessary handovers. However, the UL-HO scheme significantly minimizes the HO rate at 20ms periodicity across all speeds because of higher reduction in HOF rates and PP rates (see Fig. 7 and Fig. 8 for details). Especially, at higher speeds (i.e. 60 km/h and 90 km/h) and high periodicities (i.e. 60 ms and 80 ms), the reduction in HO rate using UL-HO is insignificant. This is linked to three reasons. First reason is the high

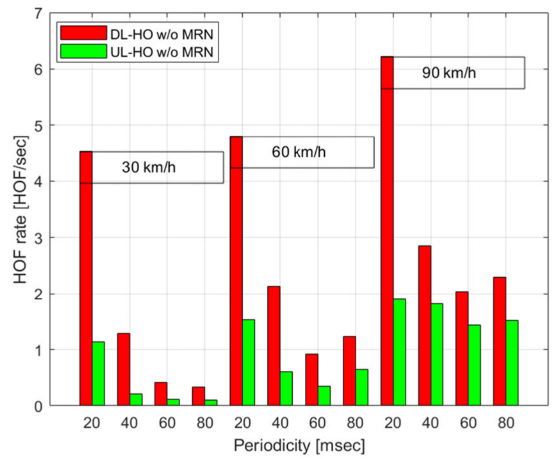

FIGURE 7. Impact of varying UE Speed and UL/DL RS periodicity on the HOF rate (without MRN).

PP rate noted for these cases in Fig. 8 where it is shown that both DL-HO and UL-HO almost have the same PP rate. Another reason is the high TTT values at high periodicities that keep the UE connection with the s-BS for a longer time thus a significant reduction in HO rate cannot be achieved even when the UL-HO eliminates the MeasReport signalling (i.e., TTT is three times the periodicity, see Table 2 for details). The last reason is linked to the UEs on-board that have poor radio link conditions, adding more HO count. Finally, as the periodicity increases, the HO rate reduces for all speed cases because of the fact that less often we measure the RS, the lower will be the HO rate especially for the UEs on-board located at the cell edges of the macro BSs having poor radio link conditions. In short, when we have a scenario where a cluster of UEs are traveling at the cell edge and we do not have a MRN to support the cell edge users, the UL-HO can significantly reduce the HO rate if we optimize the periodicity to 20 ms, for all evaluated speeds. With the UL-HO scheme, the average reduction in the HO rate is between 5% and 11%, depending on the speed.

The HO failure (HOF) rate is defined as the total number of HOF events ($\boldsymbol{N_{HOF,total}}$) divided by the simulation time ($\boldsymbol{T_{sim}}$). The HOFs are captured in the simulator mainly because of the following categories,

- Radio link failure (RLF) declared by L1 at the UE after timer T310 expiry
- Radio link control (RLC) is unable to deliver a radio resource control (RRC) message after a (max.) number of retransmission attempts (applies to MeasReport and HOconf messages)
- RACH failure after timer T304 expiry

One can formally define the HOF rate ($\boldsymbol{R_{HOF}}$) as:

$$R_{HOF} = \frac{N_{HOF,total}}{T_{sim}} = \frac{N_{RLF} + N_{RLC,fail} + N_{RACH,fail}}{T_{sim}}, \tag{5}$$

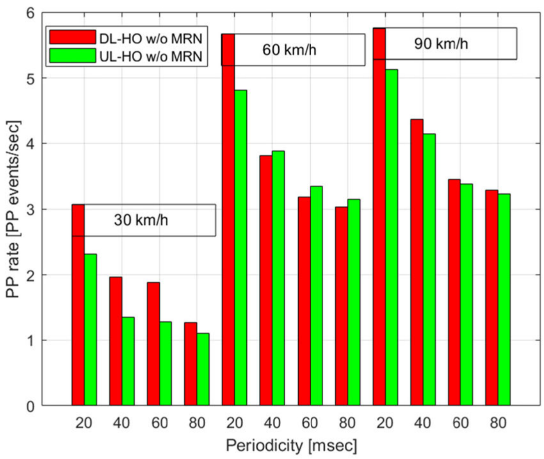

FIGURE 8. Impact of varying UE Speed and UL/DL RS periodicity on PP rate (without MRN).

where N_{RLF} is the total number of RLF failures, $N_{RLC,fail}$ is the total number of RLC failures and $N_{RACH,fail}$ is the total number of RACH failures, counted during T_{sim}.

The HOF rate for different UE speed and UL/DL RS periodicities is presented in Fig. 7. The graph shows that the UL-HO scheme reduces the HOF rate significantly, especially for low periodicities (i.e. 20 ms) since the HOFs due to MeasReport transmission or reception are avoided. This reduces HO delays and the UL-HO completes before the UE loses its connection with the s-BS, further reducing the overall HOFs. Another trend of the graph reveals that increasing the periodicities follow a decreasing trend for speed 30 km/h but for higher speed (i.e. 60 km/h and 90 km/h), the HOF rate reduces until a periodicity of 60 ms and then it again start increasing. This is because, at high speed with high periodicity (i.e. 80 ms), longer TTT values keep the UE connection with the s-BS and eventually leads to high HOFs. We argue that very frequent RSs trigger frequent HOs and HOFs, due to frequent re-assessing of A3 event conditions, whereas very infrequent RSs trigger HOFs due to RLF resulting from the unavailability of recent measurements. We observe a trade-off between HOFs and PP rate at higher speeds (i.e. 60 km/h and 90 km/h) and high periodicities that reduce the UL-HO gain in terms of HO rate (see Fig. 6 for details). This trade-off is in-line with the works presented in [29]–[33] that shows reducing the HOFs would increase the PP rate. The UL-HO scheme provides an average HOF rate reduction of 50% to 76% on average in comparison to DL-HO, depending on the speed.

The ping pong (PP) rate (R_{PP}) is defined as the total number of ping pong events (N_{PP}) divided by the simulation time (T_{sim}), i.e:

$$R_{PP} = \frac{N_{PP}}{T_{sim}}. \tag{6}$$

In turn, a ping pong event is the occurrence of a HO between a serving cell and a target cell, followed by another HO to the original serving cell, all this happening under a predefined time set to 3 seconds. The impact of varying UE speed and UL/DL RS periodicities on the PP rate is presented in Fig. 8. One trend in the graph shows that increasing periodicity decreases the PP rate. This is because the less frequent we measure the DL/UL RSs, the lower will be the HO rate and thus the possibility of PPs. It is important to note that the UL-HO at speed 30 km/h and 90 km/h follow a decreasing trend but at 60 km/h the UL-HO has a high PP rate in comparison to DL-HO at high periodicities (i.e. 40 ms, 60 ms, and 80 ms). Here, we can see a trade-off the UL-HO scheme provides between the HOFs and the PP rate. We can infer that at medium speeds (i.e. 60km/h), the UL-HO significantly reduces the HOFs (see Fig. 7) but at the cost of high PP rate, as noted in Fig. 8. Also, the high PP rate reduces the UL-HO gain in terms of HO rate in comparison to speed 30 km/h as we have seen in Fig. 6. Then again at the highest speed i.e. (90 km/h), the PP rate follows a decreasing trend even at high periodicities for UL-HO in comparison to DL-HO. We claim that sending infrequent UL RS reduces the chances for the cell edge UEs facing poor radio link conditions to come back to the original BS. The UL-HO provides a significant reduction in PP rate at $\{20, 40, 60\}$ ms periodicity at speed 30 km/h and for all other speeds at 20 ms periodicity. On average, the UL-HO scheme provides an average PP rate reduction of 3% to 26% in comparison to DL-HO, depending on the speed.

2) UE POWER CONSUMPTION

The total UE power consumption is measured as the sum of the power related to the MeasReport, RACH and HO confirm air-interface signalling message transmission and the HO command reception. The UE average total supply power consumption is calculated using (2) and (3). The UE power consumption as a function of speed and DL/UL RS periodicities is shown in Fig. 9. Overall, the UE power consumption increases with increasing speed because of high HO rate, HOF rate, and PP rate, as noted in Fig. 6, Fig. 7, and Fig. 8, respectively at high speeds. Fig. 9 also reveals that the power consumption of DL-HO is higher than UL-HO for all speeds and periodicities. This is because no MeasReport transmission is required using the UL-HO method and thus the UL-HO is power-efficient at the UE side in comparison to DL-HO. It is also clear from the chart that the UL-HO significantly reduces the UE power consumption especially at 20 ms periodicity case of all speeds because of the highest reduction in HO rate, HOF rate and PP rate observed in Fig. 6, Fig. 7 and Fig. 8 respectively. The lowest UE power consumption is obtained at high periodicity (i.e. 80 ms) due to the reduction in HO rate we noted in Fig. 6 caused by infrequent RS measurements. In view of the results, it can be concluded that the UL-HO procedure reduces the UE power consumption by 15% to 25% in comparison to DL-HO, depending on the speed.

3) BS POWER CONSUMPTION

The total BS power consumption is measured as the sum of the power related to HO command transmission, along with

MeasReport, RACH and HO confirm air-interface signalling message reception. The BS average total supply power consumption is calculated using (3) in combination with (1). The BS average supply power consumption at different UE speeds is exhibited in Fig. 10. Overall, the BS power consumption increases with increasing speed, similarly as we noted for the UE power consumption in Fig. 9. The trend of the graph is the same as we noted in Fig. 9 but the BS power consumption is much higher than the UE power consumption. The plot shows that the UL-HO significantly reduces the BS power consumption, especially at low periodicities because it removes the power consumption part due to the reception of the MeasReport. The UL-HO at 20 ms periodicity can reduce the average supply BS power consumption by around 500mW at speed 30 km/h, and 700 mW at speed 60 km/h and 90 km/h in comparison to the legacy DL-HO method. On average, the UL-HO scheme provides an average BS power consumption reduction of 18% to 23% in comparison to DL-HO, depending on the speed (i.e. the highest reduction is at the lowest speed, 30km/h).

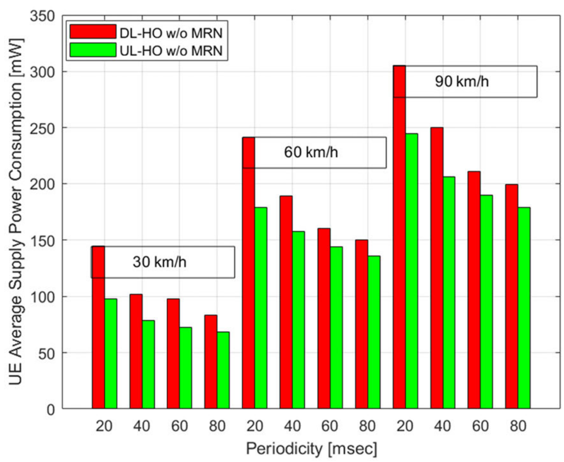

FIGURE 9. Impact of varying UE Speed and UL/DL RS periodicity on UE total average supply power consumption (without MRN).

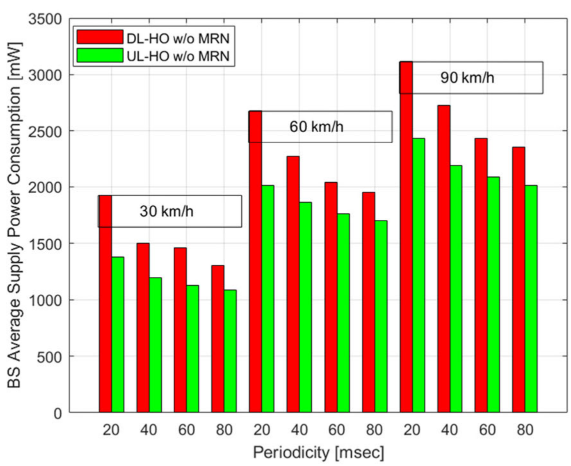

FIGURE 10. Impact of varying UE Speed and UL/DL RS periodicity on BS total average supply power consumption (without MRN).

4) REFERENCE SIGNAL TRANSMISSION AND MEASUREMENT POWER CONSUMPTION

Fig. 11 provides the impact of varying the UE speed and DL/UL RS periodicity on the DL/UL RS transmission and measurement average supply power consumption. For DL RS transmission/measurement, we assumed that one RE is required for one RSRP measurement, and for the average RSRP, we take the average over eight REs [24]. If so, the resources consumed for one RSRP measurement are eight REs for DL-HO. To measure the eight strongest cells for each UE, we use sixty-four REs. Then, we make use of (3) to find DL RS transmitted and received power consumption respectively. Similarly, we use $(N_{sc}^{RE} \times m_{SRS,0})/K_{TC}$ REs for each SRS transmission/reception, where N_{sc}^{RE} is the number of REs per symbol (12 in our case). Then, we utilize (3) to find UL RS transmitted and measurement power consumption respectively. The signalling rate for the DL RSRP and the UL RSRP measurements are obtained using the system-level simulator. The DL RS is transmitted from the BS side and received at the UE for measurement processing as shown in Fig. 3a. In contrast, the UL RS is transmitted from the UE and received at the BSs within the UL RS transmission range, and then the central network controller processes these measurements to decide which BS will serve a given UE as shown in Fig. 3b. The power consumption in Fig. 11 is the sum of DL/UL RS transmission and reception power consumption. It is to be noted that the RS power consumption remains the same for all speed values as it depends only on time (i.e. if we send a RS every 20 ms within a total simulation time of 60 sec, the power consumption remains the same for all speeds as it is independent of speed). As expected, the graph shows that the power consumption reduces with increasing periodicities because of infrequent RS transmission. Also, it expresses that the UL-HO RS power consumption is significantly lower than the DL-HO cases, almost 61% lower than the DL-HO because of lower resource consumption.

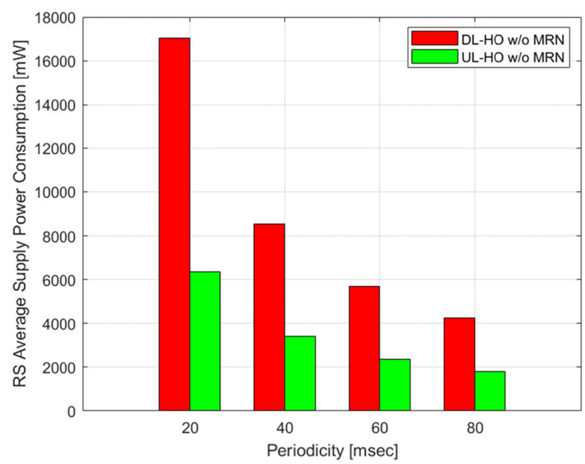

FIGURE 11. Impact of varying UE Speed and UL/DL RS periodicity on RS total average supply power consumption (without MRN).

5) TOTAL POWER CONSUMPTION

The total power consumption is the addition of both transmitted and received power consumption at the UE and BS side, i.e. the sum of Fig. 9 and Fig. 10. The impact of a varying UE speed on the total average supply power consumption is presented in Fig. 12. Specifically, we focus on the HO signalling over the air interface in both UE and BS transmissions, namely: the MeasReport, the HOcmd, the RACH, and the HOconf transmission and reception. It is to be noted that only the DL-HO procedure cases have the power consumption due to MeasReport signalling. This is because when we utilize the UL-HO procedure, no MeasReport transmission/reception is required, which reduces the overall power consumption for the UL-HO. So, the reduction of the total power consumption in Fig. 12 using the UL-HO method is linked to getting rid of the MeasReport signalling, and the reduction of overall HO rate (see Fig. 6) and HOFs (see Fig. 7). The graph shows that the power consumption due to HOcmd signalling is higher than the other signalling messages because of the higher number of resources consumed (double than the other signalling messages) for the transmission/reception of this specific signalling (see Table 2). The UL-HO scheme significantly reduces the power consumption in comparison to DL-HO especially at 20 ms periodicity case as we are able to reduce the HO rate, HOFs, and PP rate significantly for this specific case. However, the reduction in power consumption through UL-HO at high speed and high periodicities is lower because of the high PP rate we noted in Fig. 8. On average, the UL-HO scheme provides an average total power consumption reduction of 19% in comparison to DL-HO for all the simulated cases.

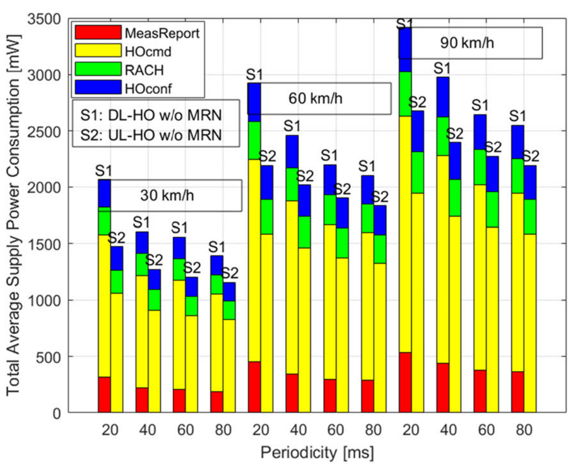

FIGURE 12. Impact of varying UE Speed and UL/DL RS periodicity on the total average supply power consumption (without MRN).

B. WITH MOBILE RELAY NODE

This section provides the gains we achieve by using MRN at the roof-top of the bus to service the UEs on-board for both the DL-HO and UL-HO.

1) HANDOVER METRICS

Fig. 13 exhibits the HO rate as a function of speed and DL/UL RS periodicities when the on-board UEs are serviced through a MRN. It can be seen from the diagram that the overall HO rate reduces significantly in comparison to Fig. 6 (with no deployed MRN). This is especially linked to the cell edge users that now have good radio link conditions because of the connection with the MRN. Notably, deploying the MRN reduces the HO rate of on-board UEs significantly if we use UL-HO as shown in Fig. 14. The HO rate of on-board UEs due to DL-HO is higher because when the MRN fails to HO to a DBS, the connection of all on-board UEs to the MRN will be lost and the on-board UEs try a connection re-establishment with the macro BSs. Using DL-HO, the MRN connected user can still suffer from frequent HOs, thus the main issue is the reliability of the backhaul link that is a SPoF. However, when using the UL-HO scheme, the MeasReport transmission/reception is not required between MRN and the DBS. This reduces the HO delay, reduces the chances

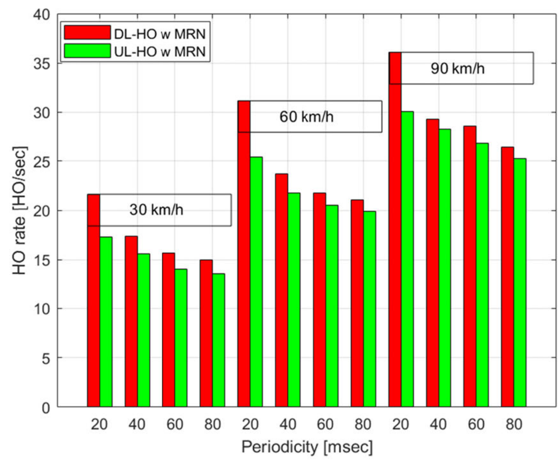

FIGURE 13. Impact of varying UE Speed and UL/DL RS periodicity on HO rate (with MRN).

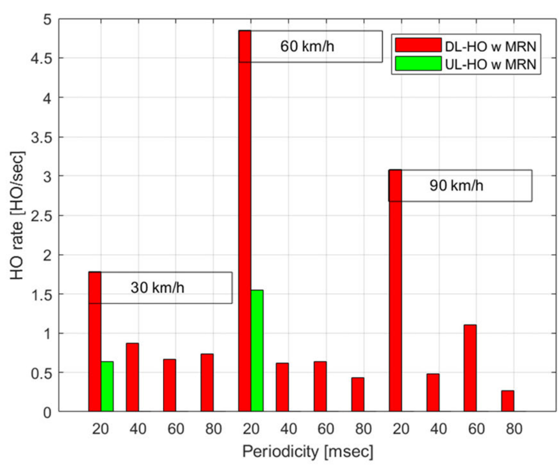

FIGURE 14. Impact of varying UE Speed and UL/DL RS periodicity on HO rate for only on-board UEs (with MRN).

of MRN SPoF, and thus, provides uninterrupted services for UEs on-board. At low speeds (i.e. 30 km/h and 60 km/h) and low periodicities (i.e. 20 ms), the UL-HO is still not able to completely avoid the on-board UEs HOs as shown in Fig. 14. This is linked to the fact that the more often the MRN transmits the UL RS, the more are the chances of MRN SPoF. But the UL-HO scheme managed to eliminate the on-board UEs HOs even at low periodicity cases of high speed (i.e. 90 km/h). This is because the high speed helps the MRN to escape from poor radio link condition areas and thus eliminates the chance of a MRN HOF to the DBSs. So the UL-HO with MRN provides higher gain in terms of reducing the HO rate even at high speeds and high periodicities in comparison to not deploying the MRN (see Fig. 6 and Fig. 13 for comparison) because of reduction in MRN SPoFs. Similar to Fig. 6, the UL-HO scheme significantly minimizes the HO rate especially at 20ms periodicity across all speeds. With the UL-HO scheme, the average reduction in the HO rate is between 8% and 13%, depending on the speed. The reduction in HO rate is higher when compared to the case without MRN (see Fig. 6) because of the decrease of on-board UEs' HO rate due to the deployment of a MRN (see Fig. 14).

The HOF rate for different UE speeds and DL/UL RS periodicities is presented in Fig. 15. The graph shows that deploying the MRN with the UL-HO scheme further reduces the HOF rate since the on-board UEs are now connected with the MRN with improved radio link conditions (see Fig. 7 and Fig. 15 for a comparison). Another trend provided by Fig. 15 reveals a trade-off between HOFs and PPs that is in-line with the works presented in [29]–[33]. Overall, the UL-HO with MRN significantly reduces the HOFs. But the cases where UL-HO significantly reduces the HOFs (i.e., speed 90 km/h at 40 ms periodicity) have a high PP rate in comparison to DL-HO (see Fig. 15 in combination with Fig. 16). On the other hand, if the UL-HO does not provide a significant reduction in HOFs, it manages to reduce the PP rate in comparison to DL-HO (see Fig. 15 and Fig. 16).

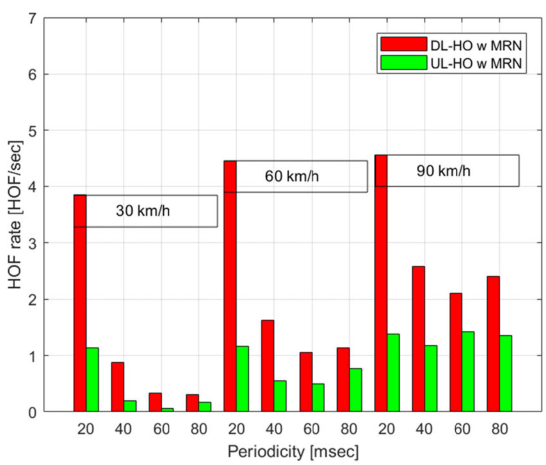

FIGURE 15. Impact of varying UE Speed and UL/DL RS periodicity on the HOF rate (with MRN).

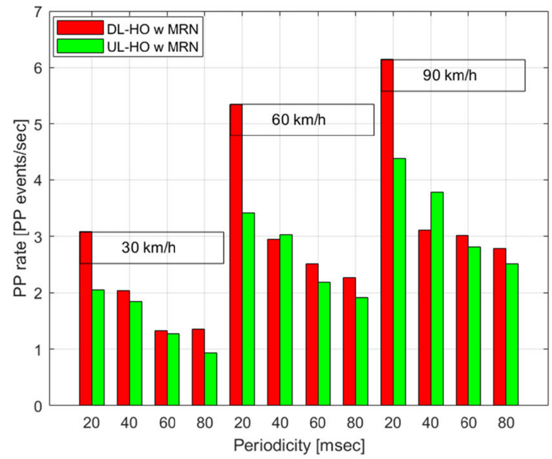

FIGURE 16. Impact of varying UE Speed and UL/DL RS periodicity on PP rate (with MRN).

On average, the UL-HO scheme with MRN provides an average HOF rate reduction of 54% to 71% in comparison to the DL-HO scheme, depending on the speed.

The impact varying UE speed and UL/DL RS periodicities on the PP rate is presented in Fig. 16. It is noted that the MRN improves the PP rate in comparison to no MRN case (see Fig. 8) which is especially linked to the improved radio link conditions of the on-board UEs due to connecting with MRN. The plot shows a trade-off that UL-HO provides between the HOFs and the PP rate, the same as we noted in Fig. 15. On average, the UL-HO scheme provides an average PP rate reduction of 10% to 22% in comparison to DL-HO, depending on the speed.

2) UE POWER CONSUMPTION

The UE power consumption as a function of speed is shown in Fig. 17. The trend of the graph is the same as in Fig. 9 but deploying MRN herein significantly reduces the UE power consumption especially when we utilize the UL-HO procedure. In this case, only the MRN performs the HO procedure on behalf of the UEs on-board and the UL-HO eliminates the chance of MRN SPoF (see Fig. 14) and thus the on-board UEs get uninterrupted services from the MRN. Also, no MeasReport transmission is required using the UL-HO method that further reduces power consumption. On average, the UL-HO scheme provides an average UE power consumption reduction of 20% to 28% in comparison to DL-HO, depending on the speed. In comparison to no MRN case (see Fig. 9), the reduction in UE power consumption is higher because of the on-board UEs power savings we achieve by using MRN.

3) BS POWER CONSUMPTION

The BS average supply power consumption at different UE speeds is shown in Fig. 18. Overall, the BS power consumption increases with increasing speed, similarly as we noted in Fig. 10 for the no MRN case. The trend of the graph is the same as we noted in Fig. 10 but the BS power consumption

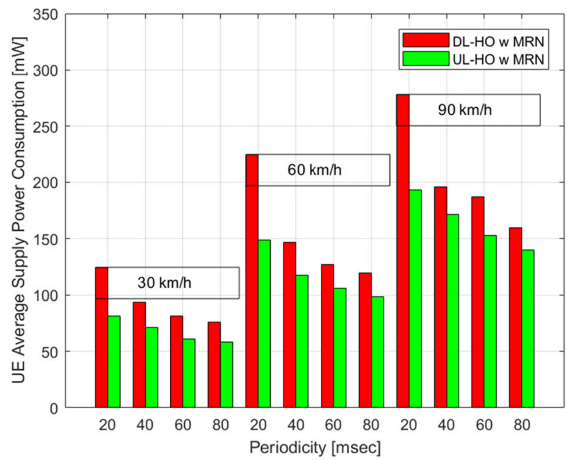

FIGURE 17. Impact of varying UE Speed and UL/DL RS periodicity on UE total average supply power consumption (with MRN).

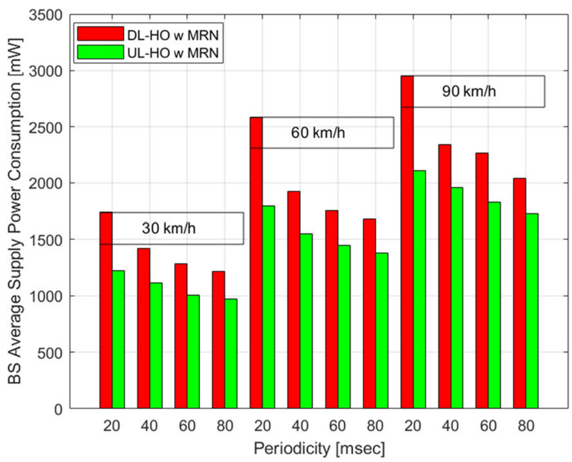

FIGURE 18. Impact of varying UE Speed and UL/DL RS periodicity on BS total average supply power consumption (with MRN).

is reduced significantly because of the MRN deployment (see Fig. 10 and Fig. 18 for comparison). The plot presents that the UL-HO with MRN case significantly reduces the BS power consumption, especially at low periodicities. This is because the UL-HO eliminates the power consumption due to the reception of the MeasReport signalling and the MRN reduces the on-board UEs HO rates (see Fig. 14) in comparison to DL-HO subsequently reducing the power consumption. The UL-HO with MRN at 20 ms periodicity can reduce the average supply BS power consumption by around 500 mW at speed 30 km/h, and 800 mW at speed 60 km/h and 90 km/h in comparison to the legacy DL-HO method. On average, the UL-HO scheme with MRN provides an average BS power consumption reduction of 20% to 24% in comparison to DL-HO, depending on the speed.

4) REFERENCE SIGNAL TRANSMISSION AND MEASUREMENT POWER CONSUMPTION

Fig. 19 shows the RS power consumption that remains the same for all speeds. The trend of the graph is the same as Fig. 11 but the RS power consumption is lower than Fig. 11.

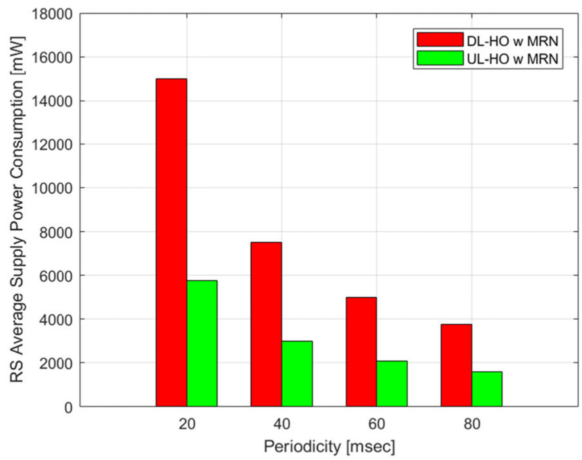

FIGURE 19. Impact of varying UE Speed and UL/DL RS periodicity on RS total average supply power consumption (with MRN).

This is linked to our assumption that the on-board UEs stop RS transmission/measurement to other BSs when they are connected with MRN to save energy [1]. Now only the MRN performs RS measurement (i.e. in DL-HO) and RS transmission (i.e. in UL-HO) on the behalf of the UEs on-board. So, the UL-HO with MRN further reduces the RS power consumption. Overall, UL-HO scheme provides an average RS power consumption reduction of 60% in comparison to DL-HO for all simulated cases.

5) TOTAL POWER CONSUMPTION

The impact of a varying UE speed on the total average supply power consumption is presented in Fig. 20. The plot shows the same trend as depicted in Fig. 12 with extra gains in terms of reducing the power consumption that we obtain by the deployment of the MRN on the roof-top of the bus. The MRN improves the radio link condition of the UEs on-board that are traveling at the cell edge of the macro BS consequently it reduces HO rates of the on-board UEs as we have seen in Fig. 14 and the total power consumption. On average, the UL-HO scheme provides an average total power consumption reduction of 22% in comparison to DL-HO for all simulated cases.

C. TOTAL POWER CONSUMPTION WITH AND WITHOUT MOBILE RELAY NODE

Fig. 21 shows the impact of a varying UE speed on the total average supply power consumption for both with and without MRN cases. At both 30km/h and 90km/h speeds: S3 (UL-HO w/o MRN) outperforms S2 (DL-HO w MRN) for all periodicities. In this way, the UL-HO saves MRN deployment and operational cost. Similarly, at speed 60km/h, S3 outperforms S2 at periodicities {20, 40}ms while other periodicities have also almost the same power consumption for both S2 and S3. Overall, the UL-HO with MRN has the lowest total power consumption for all speeds and periodicities. So, deploying a MRN with the UL-HO scheme is seems to be the most attractive solution in terms of lowest power consumption, i.e. on average 30% power consumption

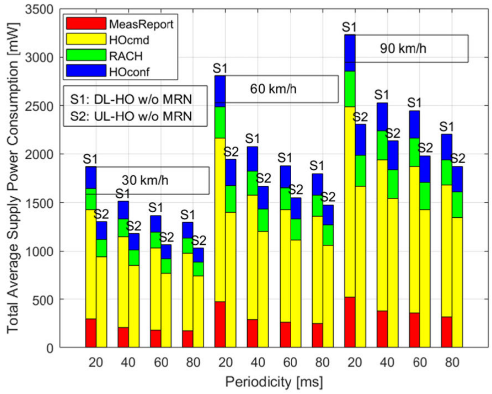

FIGURE 20. Impact of varying UE Speed and UL/DL RS periodicity on total average supply power consumption (with MRN).

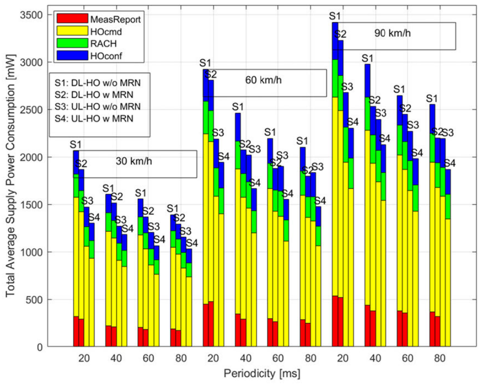

FIGURE 21. Impact of varying UE Speed and UL/DL RS periodicity on total average supply power consumption (without and with MRN).

reduction in comparison to 'DL-HO w/o MRN' for all simulated cases.

V. CONCLUSION

In this paper, a simulation analysis is presented to determine the improvements in terms of both DL-HO and UL-HO performance and the power consumption when a mobile relay node (MRN) is installed at the roof-top of a bus traveling along the cell-edge of the donor base stations (DBSs). Specifically, we exploit the UL-HO method to reduce the overall power consumption, noting in this case that no MeasReport transmission and reception signalling is required. Thus, the HO procedure completes before the UE/MRN loses its connection with the serving BS/DBS, reducing significantly the HO rate and the HOF rate. In addition, this method minimizes the HO delays and reduces the chance of the MRN single point of failure (SPoF) and thus provides uninterrupted services to the on-board UEs. High improvement in terms of HO rate, HOF rate, ping-pong rate, and power consumption is observed for the scenario where both the MRN and the UL-HO procedure is utilized. The UL-HO provides the highest reduction in power consumption especially at low periodicities (i.e., 20 ms), because of the high improvement in HO rate, HOF rate, and PP rate we observed for this specific case. In the absence of MRN, the UL-HO can reduce the HO rates by 5% to 11%, HOF rates by 50% to 76%, PP rate by 3% to 26%, UE power consumption by 15% to 26%, and BS power consumption by 18% to 23% in comparison to DL-HO, depending on the speed. Furthermore, we found an interesting trade-off between the HOF rate and PP rate. The UL-HO significantly reduces the HOFs but at the cost of an insignificant increase in PP rate especially at higher speeds. In a scenario where is cost reduction is the first priority, the UL-HO is still a suitable candidate as it outperforms without MRN in comparison to 'DL-HO with MRN' case thus reducing the OPEX and MRN deployment cost.

Deploying a MRN improves the radio link conditions of the on-board UEs but in the case of DL-HO, the MRN can still suffer from HOF to DBS causing a SPoF for the UEs on-board. In contrast, the UL-HO reduces the MRN SPoF cases through the reduction of MRN HO MeasReport signalling, thus the MRN HO completes before the MRN loses its connection with the s-DBS. For with MRN case, the UL-HO can reduce the HO rates by 8% to 13%, HOF rates by 54% to 71%, PP rate by 10% to 22%, UE power consumption by 20% to 28%, and BS power consumption by 20% to 24% in comparison to DL-HO, depending on the speed. The high improvements in the HO performance metrics are linked to the applicability of UL-HO to the MRN that reduces the on-board UEs HO rates. This makes the proposed UL-HO method more suitable for the mobile small cells (especially in the form of MRNs) to support power-efficient group mobility in future releases of the 3GPP standards heading towards higher frequencies and denser network deployments.

In the future, we will propose a UE specific periodicity selection procedure (e.g. UE closer to cell border will have low periodicity) to improve the network performance and further reduce the power consumption. Also, we will propose an SRS power control procedure to allocate the SRS power according to UE location (i.e. cell centre, cell edge) to save energy by allocating low SRS transmission power to the UEs/MRNs close to BSs/DBSs.

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