Extending Communication Range with 5G NR Multi-Hop UE-to-UE Relays

Samantha Gamboa[†‡], Thomas R. Henderson[†‡], Wesley Garey[*], Chunmei Liu[*], Richard Rouil[*]
[*]*National Institute of Standards and Technology*, Gaithersburg, MD, USA
[†]*Associate, National Institute of Standards and Technology*, Gaithersburg, MD, USA
[‡]*Prometheus Computing LLC*, Bethesda, MD, USA
{samantha.gamboa, thomas.henderson, wesley.garey, chunmei.liu, richard.rouil}@nist.gov

***Abstract*—This paper describes how fifth-generation (5G) New Radio (NR) sidelink (SL) multi-hop UE-to-UE (U2U) relays can extend communication range in off-network scenarios, where UE denotes User Equipment. We focus on key challenges introduced by SL's distributed resource allocation (Mode 2) in multi-hop topologies, particularly when semi-persistent scheduling (SPS) is used. We use system-level simulations to evaluate a tactical scenario with mission-critical push-to-talk (MCPTT) traffic over a multi-hop U2U topology. Our results show how compounded intra-path interference and losses due to half-duplex operation can degrade end-to-end communication performance. We further identify specific scheduling configuration settings that influence these effects and impact the attainable communication range.**

***Index Terms*—New Radio (NR), Sidelink (SL), Proximity Services (ProSe), multi-hop UE-to-UE (U2U) relay**

I. INTRODUCTION

Direct communication between User Equipment (UE) over the sidelink (SL) was first standardized by the 3rd Generation Partnership Project (3GPP) for Long Term Evolution (LTE) in Release 12 and later extended to 5G New Radio (NR) in Release 16. Two service verticals leverage SL capabilities: Proximity Services (ProSe) and Vehicle-to-Everything (V2X) communication. A key ProSe functionality is the UE-based relay communication, using either UE-to-Network (U2N) relays or UE-to-UE (U2U) relays [1]. U2N relays extend network coverage to remote UEs in areas with limited or no service. U2U relays enable infrastructure-independent, direct communication between otherwise out-of-reach UEs. Fig. 1 illustrates the different UE-based relay variants used for Internet Protocol (IP) communication, ranging from the single-hop architectures standardized in Release 17 and Release 18 to the multi-hop architectures currently under standardization in Release 19 [2].

Support for off-network multi-hop relay communication is essential for military and public safety operations when long-range communication is critical for situational awareness, team coordination, and operational continuity. For example, personnel may be deep inside buildings or subterranean environments during urban clearance or reconnaissance missions, or deployed across wide geographic areas during tactical maneuvers or emergency response operations [3], [4]. In these scenarios, multi-hop UE-based relaying allows data to be forwarded across multiple UEs, extending communication range without relying on fixed infrastructure and thus supporting mission-critical operations in dynamic environments.

In this paper, we focus on the SL resource allocation scheme employed for off-network multi-hop U2U relay operation. As shown in Fig. 1, communication occurs over the SL channel between the end UEs and the U2U relays, and among the U2U relays within the Mobile Ad Hoc Network (MANET). A key aspect of off-network operation is that UEs rely on pre-configured settings and self-allocated resources to communicate over the SL (Mode 2). Our evaluation shows that, under this mode of operation, intra-path interference and half-duplex conflicts between adjacent multi-hop U2U relays can limit end-to-end communication performance, and that these effects compound as the number of relays in the communication path increases. We identify key scheduling configuration parameters, such as the resource selection window length, number of retransmissions, and sensing-based resource exclusion strategies, that influence these effects and the attainable communication range extension in tactical scenarios.

In Section II, we review related literature on Mode 2 NR SL resource allocation and semi-persistent scheduling (SPS) used for periodic traffic such as mission-critical voice communication. We address the specific needs and challenges of using Mode 2 and SPS in a multi-hop U2U relay context in Section III. In Section IV, we illustrate these challenges through system-level simulations of a tactical scenario, highlighting how different scheduling parameters and network configurations impact application performance and the effective communication range achieved with multi-hop U2U relays.

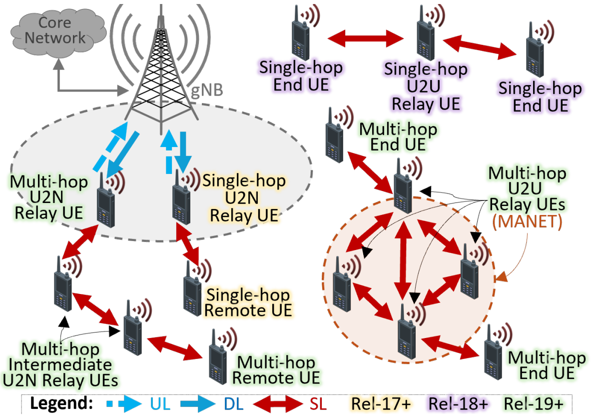


Fig. 1: NR ProSe UE-based relay architectures for IP traffic.

II. RELATED WORK

While SL was originally introduced to support ProSe, the rapid rise of V2X communication as a key vertical has significantly influenced its development. As a result, much of the existing literature focuses on the performance of V2X applications over the SL.

The authors in [5] present an analytical model characterizing packet delivery ratio performance for vehicle UEs using the SPS in LTE SL Mode 4 for V2X broadcast communication. While their model is for the LTE SL, their characterization of collisions, hidden-node effects, and half-duplex operation still apply to NR SL in Mode 2 and we build upon them in the next section. Many works focus on adapting the SPS algorithm to improve SL performance in V2X. For example, the authors in [6] propose to adaptively select the SPS resource reservation interval (RRI) based on local conditions to reduce the risk of collisions for periodic broadcast V2X safety messages. The authors in [7] propose enhancements to the sensing based resource selection to further exclude resources and avoid potential collisions when transmissions with different RRI are expected. However, these studies consider only direct SL transmissions without the involvement of relaying UEs and, therefore, do not capture the additional challenges introduced by multi-hop U2U relay scenarios.

Only a few works consider multi-hop relaying over the SL in V2X scenarios. In [8], the authors evaluate forwarding mechanisms for emergency messages that are disseminated via multi-hop broadcast to nearby vehicles over the SL. They assess the impact of such mechanisms on the collision probability of concurrent periodic traffic but do not consider sidelink-specific mechanisms beyond using separate resource pools for different traffic types. In vehicle platooning, control messages are forwarded through successive platoon members. The authors in [9] aim to reduce the end-to-end propagation delay of these messages by refining the SPS resource selection procedure. Similarly, the authors in [10] highlight the critical impact of packet drops caused by half-duplex operation in multi-hop platooning. To mitigate this, the authors propose a neighbor-aware resource exclusion scheme that uses sensing information from both previous and next hops to eliminate all resources in the corresponding slots, thereby avoiding simultaneous transmissions. This provides a key insight for multi-hop relaying, and in Section IV-C4, we show the performance of a generalized version of this approach, where all slots with sensed activity are excluded.

To the best of our knowledge, our previous work evaluating the performance of single-hop U2N relays for tactical communications [11], and developing system-level simulations for public safety applications over SL [12], are the only studies specifically focused on ProSe use cases involving UE-based relays. In this paper, we extend that work to examine SL usage for multi-hop U2U relaying, highlighting the inherent challenges and trade-offs associated with SL Mode 2 resource selection.

III. 5G NR MULTI-HOP U2U RELAY

In the 5G NR ProSe architecture for multi-hop U2U relay communication, a source end UE connects to a target end UE through one or more multi-hop U2U relay UEs within a MANET [1]. In this architecture, UEs perform ProSe multi-hop U2U relay discovery to identify nearby nodes: end UEs detect relays advertising connectivity services, while U2U relays discover neighboring relays to build the MANET. Once discovery is complete, unicast links are established over SL at the ProSe layer directly between adjacent UEs forming the network topology illustrated in Fig. 1. Each of these unicast links requires proper lower-layer configuration, including resource scheduling, to enable successful SL communication. At the network layer, an IP-based MANET routing protocol evaluates link-state information and selects the optimal path for data forwarding from the source to the target UE through the network topology.

A. NR SL resource allocation (Mode 2)

As discussed earlier, in off-network scenarios, UEs operate using preconfigured parameters and self-allocated resources, referred to as Mode 2, rather than relying on network-scheduled resource allocations as in Mode 1. In NR SL Mode 2, two types of resource scheduling mechanisms are defined: per-packet scheduling and semi-persistent scheduling (SPS). Per-packet scheduling, which is better suited for irregular traffic, involves dynamically selecting resources for each data transmission. In contrast, with SPS, a UE periodically reserves radio resources for the current and some number of future transmission opportunities, making it well-suited for applications with regular, predictable traffic patterns. This includes certain types of V2X safety messages, as seen in the previous section, and mission-critical voice applications where audio codecs generate steady, periodic traffic.

Regardless of scheduling type, upon resource selection triggering (time n in Fig. 2), the scheduler determines the number of resources required for transmission. This depends primarily on the size of the data packets to be transmitted and the Modulation and Coding Scheme (MCS) selected for the transmission. The scheduler then randomly selects resources from a pool defined in frequency by the set of available subchannels and in time by the selection window, which is bounded by the parameters T_1 and T_2, as depicted in Fig. 2.

Fig. 2: Example NR SL selection window for scheduling.

Resources where the UE previously transmitted, as well as those where it sensed transmissions from other UEs, can be excluded prior to selection if applicable. When using SPS, the periodicity of reserved transmissions allows sensing to be more effective in predicting and excluding occupied resources, thereby reducing the risk of collisions.

If retransmissions are used for improved reliability, the scheduler must reserve resources for all transmissions (n_{TX}) within the selection window, including the initial transmission and any potential retransmissions. Two retransmissions schemes are supported in the NR SL: Blind and Feedback-based (FB) Hybrid Automatic Repeat reQuest (HARQ). With the Blind scheme, all (re)transmissions are scheduled and transmitted with no feedback. With the FB HARQ scheme, retransmissions are transmitted or suppressed depending on whether or not feedback is received.

The selected resources determine the configuration of the physical layer channels: Physical Sidelink Control Channel (PSCCH), Physical Sidelink Shared Channel (PSSCH), and Physical Sidelink Feedback Channel (PSFCH). The PSCCH carries control information, such as PSSCH indication, MCS, and HARQ-related parameters, needed to decode PSSCH transmissions. A PSCCH control message can indicate up to three PSSCH transmissions, and is sent in the initial symbols of the same resource as its first associated PSSCH transmission. The PSSCH transports user data (e.g., IP packets), and the PSFCH is used to transmit HARQ feedback from the receiving UE back to the transmitting UE. When FB HARQ is used, time gaps are required between PSSCH transmissions to allow for feedback reception and processing.

In SPS, once resources are selected, they are periodically reused based on the configured RRI. The UE continues using the same resources for a predefined number of transmissions, which is determined by a randomly selected reselection counter. Once this counter reaches zero the UE may trigger the resource reselection process.

B. SPS in multi-hop U2U relay

Data loss in NR SL can occur for several reasons. First, NR SL UEs only support half-duplex communication, therefore a UE will be unable to receive transmissions while transmitting, leading to missed receptions. Second, decoding failures may occur when the signal-to-interference-plus-noise ratio (SINR) is too low, which can result from propagation loss, fading, or interference from concurrent transmissions on the same resources. Such failures can affect either the PSSCH (data channel) or the PSCCH (control channel). Notably, if the PSCCH is not successfully decoded, all associated PSSCH transmissions are also lost, as the receiver lacks the necessary control information to locate and decode the PSSCH.

In non-relay SL communication scenarios, interference and losses due to half-duplex limitations may occur due to independent transmissions, where each UE sends its own data. In contrast, in multi-hop U2U relay scenarios, they can arise within the same traffic flow as it is forwarded across multiple relays, making losses along the path damaging to end-to-end communication. For example, two distinct conflicts can arise if we consider three consecutive U2U relays in a multi-hop communication path. First, if the 1st relay and the 2nd relay transmit in the same time slot, the 2nd relay will be unable to receive the 1st relay's transmission due to the limitations of half-duplex communication, resulting in packet loss. Second, if the 1st relay and the 3rd relay, being outside each other's sensing range, select overlapping resources (hidden node problem), this may prevent the 2nd relay from decoding the transmission due to intra-path interference. Although the randomness inherent in the resource selection process helps spread transmissions and reduce collision probability, this deconfliction can be compromised in multi-hop forwarding chains, where the short forwarding intervals between relays cause their transmissions to cluster closely in time, increasing the likelihood of resource conflicts. These issues are compounded with SPS, as the same conflicting resources may be repeatedly reused over multiple intervals before reselection occurs. Moreover, conflicts can occur at multiple points along the communication path, and their cumulative impact, as shown in the next section, increases with the number of relays.

Sensing-based (SB) resource exclusion can help mitigate these issues, but its effectiveness depends heavily on the availability of sufficient uncontended resources in the pool as well as the completeness of sensing information. In practice, UEs can operate with partial or outdated knowledge of the surrounding resource usage. For example, if a neighboring UE does not transmit during the sensing window, its activity will go undetected. This is possible when the neighboring UE reselects resources outside of the sensing window, performs a simultaneous transmission, or changes its traffic pattern. It is also possible for the sensing UE to fail to decode a PSCCH message. In such cases, the sensing UE cannot identify or exclude the corresponding PSSCH resources during the resource (re)selection procedure, increasing the likelihood of interference or losses due to half-duplex communication.

IV. EVALUATION

The performance and configuration of a large scattered MANET can be difficult to evaluate without an understanding of key parameter sensitivities, so we designed our evaluation scenario to first focus on a linear topology to assess the maximum communication range extension that multi-hop UE-to-UE relays can provide. As discussed in Section III, this range extension is not infinite, as each hop introduces delay and the possibility of data loss due to interference and half-duplex limitations, ultimately degrading end-to-end communication reliability. Understanding this linear scenario can be a stepping stone to understanding a more generalized node layout. Operationally, this can be mapped to a case in which two distant soldiers communicate through a MANET consisting of other soldiers or drones, and the remainder of this section is described in this context. We conduct this evaluation using an extension of the Network Simulator 3 (ns-3), described in [12], which also models 5G NR ProSe multi-hop U2U relay communication for IP-based traffic.

A. Scenario

1) Deployment: We focus on a soldier stationed at a surveillance post that must communicate with a scout soldier that is unreachable via direct communication, but is reachable through the MANET. We assume that the initial stages (ProSe multi-hop U2U relay discovery, ProSe unicast direct link establishment, MANET IP routing, etc.) are complete, and that the communication path between the two soldiers of interest exists as it is depicted in Fig. 3. The distance in meters between each pair of consecutive devices is given by $d_{i,j}$ and is randomly selected within the interval [d_{UE} - Δ_d; d_{UE} + Δ_d].

2) Application: The soldiers use 3GPP's Mission-Critical Push-To-Talk (MCPTT) application to communicate [13]. We focus on a talk session between the surveilling soldier and the target scout soldier lasting the length of the simulation (y_T). We use the Voice over IP (VoIP) traffic model in [14] to generate the surveilling soldier's MCPTT data traffic. Talk spurts are generated according to the voice activity factor (VAF) and mean talk spurt duration ($\overline{x_T}$) defined in Table I. Voice traffic (without silence) is generated following the Enhanced Voice Services (EVS) codec parameters in Table I for the duration of a talk spurt; no traffic is generated otherwise.

B. Metrics

We use the estimated **Mean Opinion Score (MOS)** for the talk session as a performance metric in our analysis [15]. This estimation predicts user satisfaction based on auditory test libraries and communication quality that takes equipment and network impairments into account. The estimated MOS is calculated at the end of the simulation using the packet loss ratio and end-to-end packet delay. We use the full-band E-model with the default configuration, assuming no echo and room noise, and applying the corresponding EVS codec impairment parameters from [16]. The MOS ranges from 1 to 4.5, with higher scores indicating greater user satisfaction.

We define **communication range** (R) as the total distance between the two end UEs in the relay path and is given by $R = (n_{\text{UE}} - 1) * d_{\text{UE}}$, where n_{UE} is the number of UEs in the path and d_{UE} is the average inter-UE distance. To ensure practical usability, the network must also satisfy a target MOS quality level to be considered a valid range. We use an estimated MOS value of 4 as the cutoff threshold to yield satisfied users. As a reference, with the model parameters considered, the estimated MOS falls below 4 if the packet loss ratio exceeds 1.5 % or the end-to-end delay exceeds 250 ms individually, and degrades further if both occur.

We also trace the causes of PSSCH transmission losses during the simulation. This distribution is used to assess how different parameters impact MOS and communication range. Note that when a packet is sent from the surveilling soldier to the target scout soldier, it must be received and transmitted on the SL by each of the relay UEs in the path to reach the destination. The outcome of each per-hop transmission and retransmission is counted towards the distribution, allowing us to assess system behavior, not application packet loss.

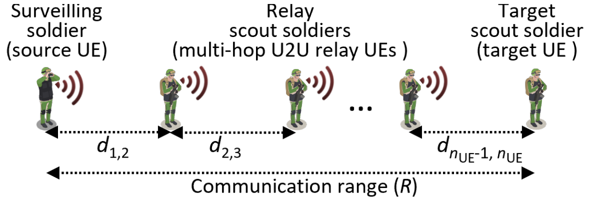


Fig. 3: Evaluation scenario.

TABLE I: Simulation Parameters.

Deployment parameters	
Number of UEs in the path (n_{UE})	[2, 16]
Mean inter-UE distance (d_{UE})	[700 m, 1100 m]
Inter-UE distance interval (Δ_d)	1 m
System parameters	
Channel fading model	Additive White Gaussian Noise
Path loss model	3GPP D2D O2O - LOS
Central frequency	793 MHz (band n14)
Bandwidth	10 MHz
Numerology (μ)	0
Subchannel size	10 Resource Blocks (RBs)
Number of subchannels (n_{SC})	5
UE Transmit power	23 dBm[1]
SL parameters	
PSSCH MCS index	[0, 6] (fixed)
Retransmission scheme	FB HARQ
PSFCH period	1 (every slot)
PSFCH total time gap	2 slots
Number of transmissions (n_{TX})	[1, 4]
Scheduling algorithm	SB-SPS with RRI = 20 ms
Guard parameters	T_1 = 2 slots
Selection window size (slots)	3 (T_2 = 4), 7 (T_2 = 8), 11 (T_2 = 12), 15 (T_2 = 16)
Application parameters	
Talk session duration (y_T)	60 s
Session Activity Factor (SAF)	1
Mean talk spurt duration ($\overline{x_T}$)	4.69 s (see [13])
Voice Activity Factor (VAF)	0.5
Voice codec	EVS
Data rate	13.2 kb/s
Packet Size	45 Bytes
Packet interarrival time	20 ms

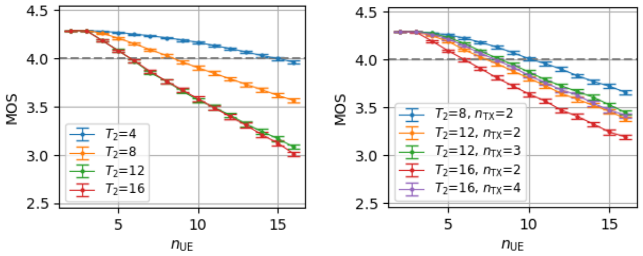
[1] Power level expressed in decibels (dB) with reference to one milliwatt (mW).

For each parameter configuration, we conducted 1000 independent simulation runs, capturing variability in the talk session traffic pattern, the SPS resource selection process, and other components of the communication stack governed by random distributions. Results are presented including the mean and 95 % confidence interval for each metric.

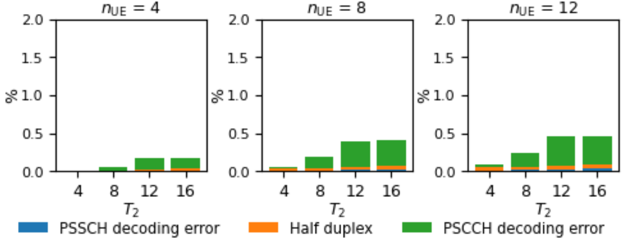
C. Results

We observe that, under favorable conditions, we can achieve considerable R with multi-hop U2U relays. For instance, Fig. 4a shows that with T_2 = 4 the system supports up to n_{UE} = 14 while maintaining MOS $>$ 4. However, performance varies significantly under less favorable conditions and system settings as shown throughout this section.

Throughout our evaluation, we observed that end-to-end packet delay increased linearly with n_{UE}, but remained negligible in terms of MOS for the evaluated scenarios. Conversely, packet loss is the main contributor to performance degradation, and we next show how system parameters can affect it.

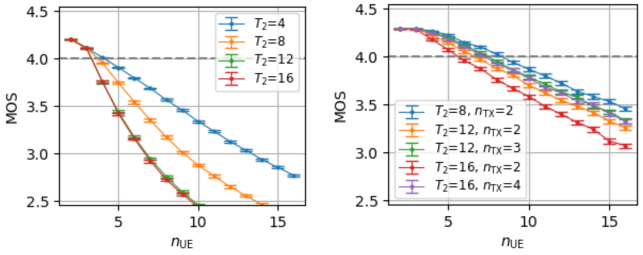


(a) MOS (n_{TX} = 1) (b) MOS ($n_{\mathrm{TX}} > 1$)

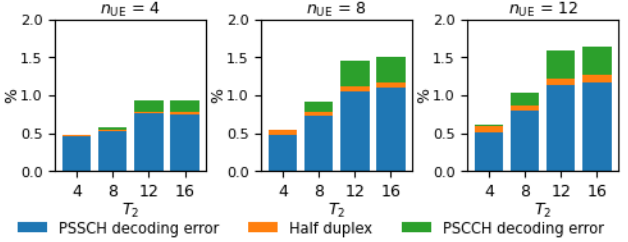


(c) PSSCH loss distribution by cause (n_{TX} = 1)

Fig. 4: Evaluation results for MCS 0 and d_{UE} = 800 m.



(a) MOS (n_{TX} = 1) (b) MOS ($n_{\mathrm{TX}} > 1$)



(c) PSSCH loss distribution by cause (n_{TX} = 1)

Fig. 5: Evaluation results for MCS 0 and d_{UE} = 880 m.

1) Impact of inter-UE distance: Smaller d_{UE} represent interference-limited scenarios, where propagation losses are negligible and performance degradation is mainly due to collisions. An example of such a configuration is illustrated in Fig. 4. With only a single data flow present in the scenario, collisions result solely from intra-path transmissions, where different relays forwarding earlier or later packets along the same communication path, use overlapping resources and create destructive intra-path interference. For $n_{\mathrm{TX}} = 1$, the PSCCH and PSSCH are transmitted in the same resource. While interference affects both channels, the receiver attempts to decode the PSCCH first, and a failure at this stage causes the entire transmission to be lost. This explains why most losses in Fig. 4c are attributed to PSCCH decoding errors.

Conversely, larger d_{UE} correspond to range-limited conditions, where packet loss is primarily driven by signal attenuation. An example of such a configuration is shown in Fig. 5. The relatively low occurrence of PSCCH decoding errors in Fig. 5c indicates that the control channel, which is generally more robust, remains decodable, while the associated PSSCH data channel fails more often due to insufficient SINR, making PSSCH decoding failures the primary source of loss.

Importantly, Figs. 4a and 5a show that the attainable R is limited, as the estimated MOS declines as n_{UE} increases in both interference-limited and range-limited scenarios. This degradation is explained by Figs. 4c and 5c, which show that decoding failures and half-duplex issues accumulate along the multi-hop path as n_{UE} increases, with additional hops introducing more losses.

2) Impact of selection window length: We evaluated four equally spaced values of T_2, resulting in different resource selection window lengths constrained by the interarrival time of application-layer packets (see Table I). As shown in Figs. 4c, 5c, 6c, and 6d, increasing T_2 leads to a higher rate of PSSCH losses in all scenarios with $n_{\mathrm{TX}} = 1$, and thus degraded MOS and limited R. Longer selection window increases the likelihood of resource pool overlap between consecutive transmissions along the path. As T_2 grows, adjacent relays are more likely to independently select overlapping resources, exacerbating intra-path interference and decoding errors, with diminishing performance degradation beyond $T_2 = 12$.

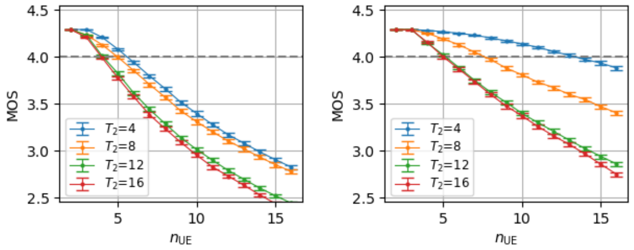
However, larger T_2 are required when using retransmissions. Beyond ensuring the selection window can accommodate the configured n_{TX}, FB HARQ also imposes PSFCH timing constraints, requiring (re)transmissions to be spaced out for feedback reception and processing. Thus, not all T_2 and n_{TX} combinations are feasible. In fact, the evaluated system and PSFCH configuration in Table I constrain the feasible settings to those shown in Figs. 4b and 5b.

3) Impact of retransmissions: Ideally the use of retransmissions increases the per-hop communication range, although with diminishing returns as n_{TX} increases, as shown in Table II. However, in multi-hop relay scenarios, PSSCH losses due to half-duplex communication and intra-path interference reduce the number of usable retransmissions for recovery. Nonetheless, retransmissions are particularly beneficial under range-limited conditions, where they help to decrease loss and improve MOS. Fig. 5b shows for example, that R can be extended from $n_{\mathrm{UE}} = 4$ (with $n_{\mathrm{TX}} = 1$ and $T_2 = 4$) to $n_{\mathrm{UE}} = 8$ (with $n_{\mathrm{TX}} = 2$ and $T_2 = 8$). In interference-limited scenarios, retransmissions also help with loss recovery for large T_2 values. For instance, with $T_2 = 16$, R improves from $n_{\mathrm{UE}} = 5$ ($n_{\mathrm{TX}} = 1$) to $n_{\mathrm{UE}} = 8$ ($n_{\mathrm{TX}} = 4$), as shown in Fig. 4b. However, the maximum R for that scenario is achieved without retransmissions and a short selection window: $n_{\mathrm{UE}} = 14$ with $n_{\mathrm{TX}} = 1$ and $T_2 = 4$, which minimizes selection window overlap and inter-path interference.

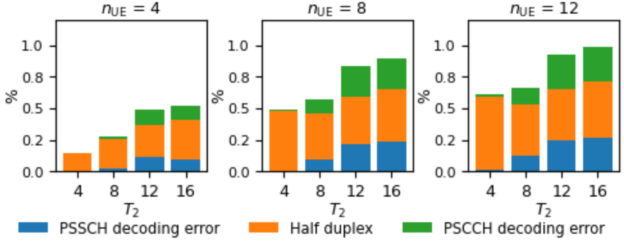
4) Impact of MCS: The MCS used for transmissions affects both transmission robustness and the spectrum required to transmit a fixed-size packet ($n_{\mathrm{SC}}^{\mathrm{pkt}}$), such as a voice packet. The

	Largest d_{UE} (m) with MOS $>$ 4 (Satisfied+)						
n_{TX}	**MCS 0**	**MCS 1**	**MCS 2**	**MCS 3**	**MCS 4**	**MCS 5**	**MCS 6**
1	880	800	860	820	780	860	820
2	980	900	960	880	840	940	880
3	1020	960	1000	940	880	980	920
4	1040	980	1020	960	900	1000	940
$n_{\text{SC}}^{\text{pkt}}$	3	3	2	2	2	1	1

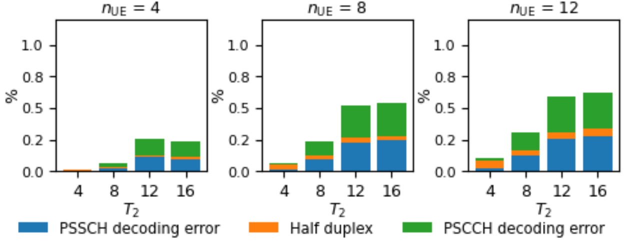
TABLE II: Direct (n_{UE} = 2) communication range estimation for different MCS and n_{TX} values. The required number of subchannels for packet transmissions ($n_{\text{SC}}^{\text{pkt}}$) are also shown.



(a) MOS (no slot exclusion) (b) MOS (slot exclusion)



(c) PSSCH loss distribution by cause (no slot exclusion)



(d) PSSCH loss distribution by cause (slot exclusion)

Fig. 6: Evaluation results for MCS 2, d_{UE} = 800 m, n_{TX} = 1.

trade-off between range and spectral efficiency can be observed in Table II where MCS indices with equal $n_{\text{SC}}^{\text{pkt}}$ have different estimated direct communication range, with more robust MCS indices (lower index) having longer ranges.

When SB resource exclusion is used, UEs exclude individual sensed resources from selection. With larger MCS indices, fewer resources are required per transmission, as shown in Table II, which allows selecting resources within the same slot as a previously sensed transmission. This may lead to half-duplex conflicts, which can occur at multiple points along the multi-hop U2U relay path, hindering end-to-end performance. This effect is shown in Fig. 6c for a scenario with MCS 2, where most PSSCH losses are due to half-duplex, limiting the attainable R to a maximum of n_{UE} = 5 (Fig. 6a, T_2 = 4). If instead, the resource selection is adapted to exclude all resources from the slots where a transmission has been sensed (variant of the slot exclusion strategy proposed in [10]), most of these losses are suppressed, as shown in Fig. 6d. This improves MOS and extends R up to n_{UE} = 13 (Fig. 6b, T_2 = 4).

V. CONCLUSION

To our knowledge, this work provides the first evaluation of the performance and configuration trade-offs of 5G NR multi-hop U2U relays in off-network scenarios. Using a tactical surveillance scenario with MCPTT traffic, we investigated how scheduling configuration choices impact communication quality and attainable range. Even with a controlled but operationally relevant relay topology, the results reveal a complex trade space involving MCS selection, resource selection window size, resource exclusion scheme, and retransmission strategies, with different configurations proving optimal under interference-limited versus range-limited conditions. These findings provide key insights for designing adaptive SL scheduling mechanisms to support reliable multi-hop communication in tactical and public safety deployments.

REFERENCES

[1] 3GPP, "Proximity based Services (ProSe) in the 5G System (5GS) (Release 19)," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 23.304, 12 2024, v19.2.0.

[2] ——, "Proximity-based Services in 5GS – Phase 3," 3rd Generation Partnership Project (3GPP), Work Item Description SP-240988, 06 2024.

[3] National Spectrum Consortium, "Introducing additional mission-critical use cases for 5G Sidelink, technology gaps and proposed enhancements," 3rd Generation Partnership Project (3GPP), TDoc RP-223388, 12 2022.

[4] FirstNet, "ProSe Multi-Hop relay use cases for public safety," 3rd Generation Partnership Project (3GPP), TDoc S2-2402349, 02 2024.

[5] M. Gonzalez-Martin, M. Sepulcre *et al.*, "Analytical models of the performance of C-V2X Mode 4 vehicular communications," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1155–1166, 2019.

[6] A. Dayal, V. K. Shah *et al.*, "Adaptive semi-Persistent scheduling for enhanced on-road safety in decentralized V2X networks," in *IFIP Networking Conference (IFIP Networking 2021)*, 2021, pp. 1–9.

[7] S. Lee, H. Shin *et al.*, "Refining packet collision check in resource allocation for NR sidelink Mode 2," in *2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring)*, 2023, pp. 1–6.

[8] Z. Pei, W. Chen *et al.*, "Analysis and optimization of multihop broadcast communication in the internet of vehicles based on C-V2X Mode 4," *IEEE Sensors Journal*, vol. 22, no. 12, pp. 12 428–12 443, 2022.

[9] K. Murata, K. Sanada *et al.*, "An improved SB-SPS scheme with low transmission delay for relay transmission in vehicle platooning with C-V2X sidelink communication," in *IEEE Vehicular Technology Conference (VTC2024-Spring)*, 2024, pp. 1–5.

[10] A. Ohshima, K. Sanada *et al.*, "Enhanced SB-SPS scheme to mitigate half duplex problem for relay transmission in vehicle platooning," in *IEEE 21st Consumer Communications & Networking Conference (CCNC)*, 2024, pp. 654–655.

[11] S. Gamboa, A. Ben Mosbah *et al.*, "System-level evaluation of 5G NR UE-based relays," in *IEEE Military Communications Conference (MILCOM 2023)*, 2023, pp. 807–814.

[12] S. Gamboa, T. R. Henderson *et al.*, "Towards system level simulations of public safety applications over 5G NR sidelink," in *IEEE World Forum on Public Safety Technology (WFPST)*, 2024, pp. 1–6.

[13] W. Garey, T. R. Henderson *et al.*, "Modeling MCPTT and user behavior in ns-3," in *11th International Conference on Simulation and Modeling Methodologies, Technologies and Applications, SIMULTECH*, Online, 2021, pp. 30–41.

[14] B. Bojovic and S. Lagen, "Enabling NGMN mixed traffic models for ns-3," in *2022 workshop on ns-3 (WNS3 '22)*, Online, 2022, p. 127–134.

[15] ITU, "Recommendation G.107.2: Fullband E-model," International Telecommunication Union (ITU), Tech. Rep. G.107.2, Mar 2023.

[16] ——, "Recommendation G.113: Transmission impairments due to speech processing," International Telecommunication Union (ITU), Tech. Rep. G.113, Sep 2024.