Multi-Hop User Equipment (UE) to UE Relays for MANET/Mesh Leveraging 5G NR Sidelink

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ABSTRACT

This paper provides use cases to adapt 5G sidelink technology to enable multi-hop User Equipment (UE)-to-UE (U2U) and UE-to-Network relaying in 3GPP standards. Such a capability could enable groups of users to communicate with each other when operating at the periphery or outside a network's coverage area, with commercial and public safety benefits. This paper compares routing protocols to enable sidelink with U2U relay to support a Mobile Ad hoc Network (MANET). A gap analysis of current 3rd Generation Partnership Project (3GPP) Release 18 (R-18) specifications is performed to determine the missing procedures to enable multi-hop U2U relaying, along with a proposed candidate protocol to fill the gap. The candidate protocol can be submitted as a contribution to 3GPP TSG Service and System Aspects (SA) Working Group 2 (WG2) as proposed changes to the 5G architecture in 3GPP Release 19 (R-19).

KEYWORDS

5G, ProSe, Sidelink, Multi-hop, Relay, MANET, Mesh, Routing

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1 Introduction

Sidelink communication was introduced by the 3rd Generation Partnership Project (3GPP) in Release 12 (R-12). It leverages long term evolution (LTE) to address commercial, network offloading, assuring user experience consistency including reachability and mobility aspects, as well as public safety and mission critical use cases whereby devices, or User Equipment (UE), in proximity could perform direct communication. Various use cases of Proximity based Services (ProSe) and sidelink, the underlying communication technology for ProSe, have become popular. For example, car manufacturers can support various use cases of Vehicle to Everything (V2X) [1], and Internet of Things (IoT) devices can communicate with high efficiency and low power. In R-16, the evolution of sidelink communications continues in Fifth Generation (5G) New Radio (NR) focusing on V2X. To meet advanced use case requirements, relaying via sidelink communication was later introduced in 3GPP R-17 to extend the range of cellular coverage to the network (i.e., UE-to-Network [U2N] relaying), and in R-18 to extend the range of communication between two devices (i.e., UE-to-UE [U2U] relaying).

Current 3GPP 5G sidelink communications support only one-hop relay communication. 3GPP studied the requirements for supporting multi-hop U2N relay in Technical Specification (TS) 22.261. However, 3GPP has not considered multi-hop U2U relay yet. With a one-hop constraint for U2U relaying, this type of communication lacks the support to connect with a target UE out of the one-hop proximity of a relaying node, and this gap prevents the government from adopting sidelink technology. In public safety or other emerging mission-critical scenarios where 5G network infrastructure is not always available (i.e., in out of coverage scenarios) using 5G sidelink, should make it possible to discover and route communication to any team member with one or more hops (i.e., multi-hop) as illustrated in the seminal paper on 5G-Advanced and 6G [2].

Mobile Ad hoc Networks (MANETs), or mesh networks, are infrastructure-less networks built with mobile nodes and without a central administration to coordinate communication. Sidelink requires enhancements in a) multi-hop relays and b) routing protocols to form a MANET. A MANET leveraging, standards-based, 5G sidelink can enable a mesh topology whereby traffic can be routed via intermediate mobile nodes without fixed 5G infrastructure assistance. How to provide configuration and authentication for sidelink and relays, in out of coverage scenarios, are open problems involving tradeoffs between security, flexibility, and agility for network participants.

In addition, MANETs have an inherent interference mitigation capability by routing around zones experiencing interference (i.e., using the routes that are interference free). With this additional benefit of providing increased resilience in congested or contested networks, sidelink-based MANET is a good candidate to meet the requirements of emerging use cases including public safety and mission critical communication. Sidelink-based MANET does not have to be confined to the support of short-range use cases; for example, unmanned aerial vehicles (UAVs) acting as relays can extend the range of MANETs.

In this paper, we, the Homeland Security Systems Engineering and Development Institute (HSSEDI), introduce technical approaches to implement multi-hop U2U relay for MANET, leveraging 5G NR sidelinks. The detailed contributions can be summarized in the following:

1. First, we perform a landscape assessment of sidelink relaying in 3GPP standards.
2. Second, we compare routing protocols to enable sidelink with U2U relaying to support a MANET.
3. Third, we perform a gap analysis of current 3GPP R-18 specifications to determine the missing procedures to enable multi-hop U2U relaying. Then, we propose procedures to fill the gap to enable a MANET with multi-hop U2U relaying. HSSEDI plans to submit the proposed procedures as contributions for proposed changes for 5G architecture in 3GPP R-19. In this analysis we note some potential issues in implementing multi-hop relaying, setting the stage for future research.

2 Background

2.1 ProSe

ProSe is a term used by 3GPP Service Aspects (SA) working groups (WGs) to encompass the services required to perform sidelink communications. It involves: End-to-end procedures/services provisioning required to support sidelink communications and relaying via the ProSe Control 5 (PC5) interface including registration. Service/parameter provisioning, connection establishments (for different cast modes; layer 3 [L3] U2N relay; layer 2 [L2] U2N relay). Identification (ID) management (for different cast modes and relaying) and security provisioning. PC5 can be LTE or 5G NR based. It is a logical communication interface used for direct communications between two entities. In other words, PC5 is for U2U direct communication.

2.2 Sidelink

Sidelink is an air interface including, layer 1 (e.g., channel structure) and layer 2 (e.g., MAC [Medium Access Control]) supporting direct communications between two UEs. Sidelink is a term mainly used by 3GPP Radio Access Network (RAN) WG1 and RAN WG2.

2.3 Relay

2.3.1 UE-to-Network (U2N) Relay

U2N Relay is an intermediate node used to extend the coverage of a cell and provide reachability for cell-edge UEs (or out-of-coverage UEs) which need to communicate with the 5G system (5GS). UEs out-of-coverage or without a strong connection to the cell can perform direct communication with a U2N relay to receive services from a Protocol Data Unit (PDU) session (R-17), emergency services (R-18), or multi-path communication for enhanced data rates or reliability (R-18). 3GPP studied the requirements for supporting multi-hop U2N relay in Technical Specification (TS) 22.261.

2.3.2 UE-to-UE (U2U) Relay

The U2U relay can establish sidelink communication between two ProSe enabled UEs: source and destination when both UEs are out of coverage. Only one-hop U2U relaying is supported in 3GPP R-18.

2.4 Status of UE-to-UE Multi-Hop Relay in 3GPP SA1 WG

FirstNet submitted contributions including a proposed mini work item description (WID) (S1-231043) to update/add requirements for multi-hop U2U relaying in two 3GPP specifications, and proposed changes (S1-231044 and S1-231045) to those two specifications to 3GPP SA WG1 meeting in May 2023. The two specifications are TS 22.261 "Service requirements for the 5G system" and TS 22.280 (Mission Critical Services Common Requirements [MCCoRe]; Stage 1). The mini WID was completed, and the proposed changes were approved.

2.5 Sidelink Standards Evolutions

The following provides 3GPP standards evolutions for sidelink:

• R-12: ProSe enabled by LTE, device-to-device (D2D) supports mission-critical communications of public safety. However, it did not gain any momentum.

• R-14: LTE-V2X with introducing sidelink transmissions (~32 Mbps; broadcast communication only [there is no feedback channel; as a result, no Hybrid Automatic Repeat Request]; two new modes of resource allocation [modes 3 and 4]).

• R-15: LTE-V2X with a higher data rate (~72 Mbps; broadcast only)

• R-16: 5G NR-V2X (~200 Mbps; unicast, groupcast and broadcast; two modes of resource allocation [modes 1 and 2]).

The evolution of sidelink communications continues in 5G NR focusing on V2X. It complements LTE V2X, not to replace:

• R-17: 5G NR sidelink develops capabilities to support public safety and emergency communications, in addition to V2X. It supports in-coverage, partial coverage, and out-of-coverage scenarios. It enhances latency, Quality of Service, and power efficiency.

• R-18: 5G NR sidelink supports U2U relaying, carrier aggregation, Sidelink-Unlicensed (Sidelink-U), and others.

3. Related Work

For a MANET, there needs to be a routing protocol to exchange information for reachability, and reachability is reflected using a routing table. There are two types of routing protocols: proactive and reactive [3]. Proactive routing protocols, such as Optimized Link State Routing (OLSR), constantly update the routing information from a source to a destination. Reactive routing protocols, such as Ad hoc On Demand Distance Vector (AODV), find a route, when necessary, (i.e., when a source is required to send a packet to a destination). Proactive protocols have the advantage of lower latency when sending a packet since a route has been found. It, however, introduces more routing overhead, especially for a larger network (i.e., more hops are required for a packet to reach a destination from a source) and higher mobility for nodes (i.e., more updates to the routing information are required since network topology is changing due to mobility). Reactive protocols have the advantage of creating lower routing overhead, but the latency is much higher. Since 5G is designed for lower latency applications, only OLSR-like protocols are considered in this paper.

The following are the assumptions when discussing the features of various routing protocols. There may be a sending node, receiving node, and relaying node, where a sending node may send data to the receiving node through one or more relaying nodes. Each node may take on another role at any time.

3.1 Routing Table

Each node maintains a routing table to provide end-to-end routes between source and destination nodes. This may either mean a L2/L3 address associated with direct communication to the destination nodes or with relays providing a connection with the destination node. In the case of multi-hop relaying, there will be more than one relay in each entry in the routing table.

For devices with limited processing power, it is challenging for those devices to continuously maintain a routing table with end-to-end routes when some nodes in the route have changed their positions due to mobility. It also creates routing overhead. However, if the end-to-end routes are replaced with suitable next-hop neighbors [4], the routing table update and its associated routing overhead can be reduced. This feature will be leveraged by our proposed routing protocol.

3.2 Broadcast

A source node broadcasts a data message destined to a target node to its neighbor relays, and a neighboring relay in turn re-broadcasts the messaging to its neighbor relays, until the message reaches the target node [5]. When the target node receives the message, the target node will reply with an acknowledgement back to the source node. When a relay sees a message with the sequence number already stored in a buffer, the message will not be broadcasted anymore since it indicates this message is a duplicate. To limit the latency for a message within a certain threshold, a message can be relayed for at most N hops. One side product of this approach is there are overheads for message duplication (but also creates redundancy).

3.3 5G Integrated Access and Backhaul Backhaul Adaptation Protocol

5G integrated access and backhaul (IAB) backhaul adaptation protocol (BAP) uses a Directed Acrylic Graph/Spanning Tree approach. The routing method used by BAP might be too simple for a dynamic mesh network.

BAP is a simplistic routing protocol assuming a static configuration, and is not designed for dynamic configuration (when nodes move around). The centralized unit (CU) controls all the distributed units (DUs) attached, and is in charge of the BAP. The CU is a centralized controller responsible for setting up logical channels for the backbone. The CU possesses of all the link status, and the CU can set up a string of nodes to extend the coverage. It can also set up another string of nodes (if the previous string is blocked). For a mesh, this requires extra steps to nominate and maintain a centralized controller. In addition, a centralized controller creates a single point of failure.

4. Architecture and Proposed Routing Work

A candidate routing protocol is proposed in this section. The following provides assumptions for developing a multi-hop relay routing protocol:

- The protocol needs to discover if a destination node is reachable from a source node
- Only L2 relay is supported (it is more secure)
- All UEs are capable of relaying via initial provisioning
- All source L2 IDs are assigned via initial provisioning.

The following are the considerations for selecting a routing protocol:

- How to ensure proper security protections for mesh links?
- Does the routing protocol handle mobility of nodes well?
- What happens when one of the hops disappear? Can the routing protocol handle that?
- What is the routing overhead created vs performance of the routing protocol (e.g., latency of establishing a link)?

- With regards to the authorization to act as a U2U relay, two scenarios can be considered:

  i. Every node can choose to act as a U2U relay based on their resources or capabilities (e.g., battery, bandwidth, etc.).

  ii. Only a subset of UEs can act as a U2U relay. In other words, the resulting mesh becomes a partial mesh. This prevents collisions but there are more chances of communication failure due to fewer relaying nodes.

4.1 Proposed Routing Procedures

This section describes the proposed procedures to enhance existing 5G standards to enable a mesh leveraging multi-hop sidelink NR mode 2 U2U relaying and ProSe enabled devices. The procedures include the following aspects of a mesh network: a) UE discovery (combined with route discovery), b) Routing table update, and c) Communication via multi-hop U2U relaying.

The procedures utilize as much of the existing 5G standards as possible to maximize compatibility, (e.g., communication via multi-hop U2U relaying will leverage TS 23.304 Section 6.4.3 "Unicast mode 5G ProSe Direct Communication"). We propose combining UE discovery and direct communication together into one integrated protocol for multi-hop U2U relay. We also propose the integrated protocol becomes the third discovery protocol where the other two are open and restricted discovery protocols. Although the integrated discovery and direct communication is proposed for multi-hop U2U relay, it is also applicable to multi-hop U2N relay.

Approach requirements: Nodes need to know the data message destination. MANET can function without 5G Core; however, offline provisioning and authorizing sidelink devices are required.

Approach assumptions: The sideink devices can mutually authenticate with each other without a 5G core. The sidelink devices can use the sidelink channels for out of coverage scenarios. The sidelink devices can protect the privacy of their identifiers from unauthorized devices. The sidelink devices can provide confidentiality, integrity, and anti-replay protection of messages to be sent.

In Figure 1, the proposed approach for deploying a mesh leveraging 5G sidelink U2U relays for the out of coverage scenario is shown. The source UE makes either an Integrated Discovery Request (IDR) or Integrated Direct Communication Request (IDCR) to either U2U relay 1 or 2. Each U2U relay broadcasts the IDR to ProSe enabled UEs within its sidelink RF communication range. Each U2U relay unicasts the IDCR to its selected neighboring ProSe enabled UE. U2U relay 1 is used by source UE to discover or communicate with Destination UE 1 and requires single hop U2U relaying. Meanwhile, U2U relay 2 is used by source UE to discover or communicate with U2U relay 3 who discovers or communicates with Destination UE 2. The sidelink connection between Source UE and Destination UE 2 uses multi-hop U2U relaying.

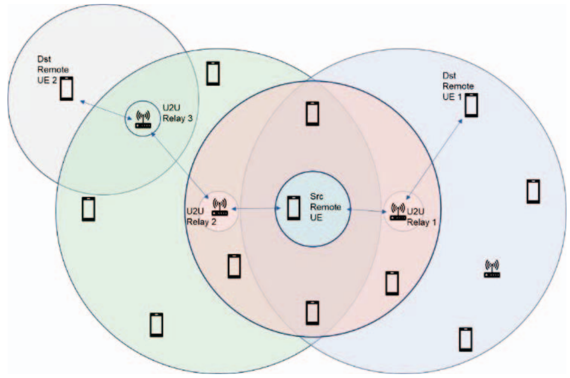

Figure 1. Proposed Approach for Deployment of 5G MANET using U2U Relays for Out of Coverage Scenario

A high-level example procedure for a source UE to discover its neighbors, and for sending a data message from a source UE to a destination UE via multi-hop relaying is discussed below. The example can be extended to other types of messages such as direct auth and key establish, direct auth and key establish response, direct security mode command, direct security mode complete, direct communication accept, and others. The steps for the L2 link establishment procedure for the unicast mode of ProSe Direct communication over a PC5 reference point in Figure 6.4.3.1-1: Layer-2 link establishment procedure [6] are used as a baseline to develop the proposed routing procedure. By comparing the baseline and the proposed procedure, the deltas represent the additional steps necessary to add 3GPP SA WG2 R-19 specifications to perform multi-hop relaying.

Step 0. During provisioning, the S-UE/D-UE and U2U relays are authorized to use and provide relay services. Security and discovery parameters are provisioned. The discovery parameters include both a set for discovering a D-UE and a set for discovering a U2U relay. Discovery parameters include the D-UE User info ID, S-UE User Info ID, Relay Service Code (RSC) and Type of Discovery message (in our proposal, this would be the IDR). The L2 ID may also be provisioned. RSC is used to specify the relay service offered/requested. The security parameters corresponding to the RSC include the code sending security parameters and code receiving security parameters required to provide the message confidentiality protection, replay protection, and integrity protection [7]. Note, the security procedure [7] is only for one-hop U2N relay, not for one-hop or multi-hop U2U relay; however, the security requirements for those two classes of relays should be similar. The following are a summary of RSC capabilities.

A U2U relay may provision multiple RSCs. RSC is provided by the Policy Control Function (PCF) or provisioned in the mobile equipment or configured in the Universal Integrated Circuit Card (UICC). Each RSC has its own security contents; however, how to authenticate an End UE or relay does not exist for U2U relay since TS 33.503 supports only R-17. RSC (and its associated security contents) is valid for a finite duration. RSC in used in the integrated discovery process. Privacy of RSC is protected.

Step 1. All UEs broadcast an IDR with S-UE ID and RSC to identify neighbors for reaching a destination, periodically. It is proposed to make relay_indication of integer data type used for relay hop count. The relay_indication is incremented by 1 with every hop (i.e., when a U2U relay rebroadcasts the IDR).

Step 2. Describing what a node should do when a node receives an IDR. S-UE, D-UE1 and D-UE2 all participate in this integrated discovery. When a node receives an IDR, its UE ID is added to the Source ID. The node checks the number of times the IDR has been rebroadcasted. If the IDR has been relayed for more than N times, the request will be dropped. If not, the relay_indication is increased by 1 with each rebroadcast of IDR, and the node rebroadcasts the IDR.

By using a selection criterion, each UE builds a suitable next-hop neighbor for reaching a particular destination. The selection criteria include: The next-hop neighbor for a destination is the node that forwarded the IDR the most from that destination (i.e., most connectivity to the destination via the next-hop neighbor based on the current topology). There is no direction to the destination indicated. With least number of hops. There is no direction to the destination indicated.

To add reliability to sending messages, each node can have more than one suitable next-hop neighbor. For example, if a node has two next-hop neighbors, a data message will be sent out by two interfaces (two neighbors) to reach its destination. And the paths to reach to a destination is increased exponentially as in a tree topology where a root is expanded to two children nodes and each children node is further expanded to additional children nodes. Note: To limit the overhead created from the routing procedure and complexity of managing the network, the maximum number of hops allowed (i.e., N) can be a smaller number (e.g., 3 or 4).

Step 2a) For S-UE. The U2U Relay 2 receives IDR from S-UE. The U2U-Relay 2 sends the IDR to its neighbors, including the U2U-Relay3. Note: during this step, the U2U-Relay 2 may send the IDR back to the S-UE, due to the nature of broadcasting. In this case, the S-UE will discard this IDR. The U2U-Relay3 receives IDR from U2U-Relay 2. The U2U-Relay 3 sends the IDR to D-UE 2. Note: during this step, the U2U-Relay 3 may send the IDR back to the U2U-Relay 2, due to the nature of broadcasting. In this case, the U2U-Relay 2 will discard this packet.

Step 2b) The same procedure also repeats for D-UE 2.

Step 2c) For S-UE, the IDR received from D-UE 2 would come from U2U Relay 2, the most compared with other on-hop neighbors. S-UE will mark U2U Relay 2 as a suitable neighbor to reach D-UE 2.

Step 2d) Similarly, U2U Relay 2 will mark U2U Relay 3 as a suitable neighbor to reach D-UE 2.

Step 2e) Similarly, U2U Relay 3 will mark D-UE2 as the direct path for reaching D-UE 2.

Step 3. S-UE and D-UE starts integrated direct communication via the U2U relays and each U2U relay uses suitable neighbors to send the data message.

Step 4. During integrated direct communication between S-UE and D-UE, the link may be lost. However, since steps 1 and 2 are performed periodically, the next-hop neighbor table will be refreshed, and the link loss can be mitigated. The time interval for repeating steps 1 and 2 are based on factors such as number of devices in the network, mobility of devices and the localized propagation environments.

5. Next Steps

The first is to develop a more comprehensive selection criterion for choosing next-hop neighbor(s). The criterion can be based on a cost function considering number of IDRs received from a destination, the number of hops reflected on the IDR, the latency of the IDR received, and the number of errored IDRs received, as well as the mission requirements including both performance and resilience.

The second is to look into the 5G enhancements for sidelink in 3GPP R-18 (e.g., carrier aggregation, beam forming, and support of unlicensed bands) as additional benefits for using sidelink technologies and their impact to the routing procedure. As an example, the routing procedure may need to be enhanced when considering directionality of a node and mobility. Those enhancements can increase the data rate, provide resilience capability, and provide flexible deployments in different areas using unlicensed band.

The third is to perform modeling and simulation (M&S) to evaluate the performance of the proposed procedure. The M&S effort would leverage Network Simulator-3 simulations built from National Institute of Standards and Technologies and the University of Washington.

The fourth is to conduct lab prototyping and demonstration for a proof of concept by working vendors such as Qualcomm and open-source implementations operating on Software Defined Radios.

The fifth is based on the results from M&S and lab prototyping, submit contributions to 3GPP standards to add multi-hop U2U relays and a routing protocol to enable multi-hop U2U relays to become a MANET.

The 5G IAB has the capability of connecting a few gNBs with multi-hop relays without physical cables. HSSEDI will investigate adding 5G IAB for constructing an optimal MANET topology leveraging different tiers of multi-hop capabilities based on infrastructure-based IAB and infrastructure-less sidelink [8].

6. Conclusions

Sidelink communication was introduced by the 3GPP R-12 leveraging LTE to address commercial (e.g., in V2X), network offloading, assuring the consistency of the user experience as well as public safety and mission critical use cases whereby devices, or UE, in proximity could perform direct communication. In R-16, the evolution of sidelink communications continues in 5G NR with focus on V2X. To meet advanced use case requirements, relaying via sidelink communication was later introduced in 3GPP R-17 to extend the range of cellular coverage to the network (i.e., U2N relaying) and in R-18 to extend the range of communication between two devices (i.e., U2U relaying). Current 3GPP 5G sidelink communications supports only one-hop relay communication. One-hop relay needs to be extended to multi-hop relay to fully support the requirements of public safety and mission critical use cases and is a fundamental capability for supporting MANETs.

For this paper, HSSEDI performed a landscape assessment of sidelink relaying in 3GPP standards. We compared routing protocols to enable sidelink with multi-hop U2U relaying to support a MANET. We performed a gap analysis of current 3GPP R-18 specifications to determine the missing procedures to enable multi-hop U2U relaying. We proposed procedures to fill the gap to enable a MANET with multi-hop U2U relaying. The proposed procedures are flexible in design and can be configured to support requirements in latency, throughput, reliability and mobility for a MANET. HSSEDI recommends the Department of Homeland Security, representing the interests of the public safety community, partner with other agencies who may benefit from these technologies and then begin on the next steps as outlined in this paper including engaging the 3GPP standards bodies who may have commercial interests in these technologies as well.

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The Homeland Security Act of 2002 (Section 305 of PL 107-296, as codified in 6 U.S.C. 185), herein referred to as the “Act,” authorizes the Secretary of the Department of Homeland Security (DHS), acting through the Under Secretary for Science and Technology, to establish one or more federally funded research and development centers (FFRDCs) to provide independent analysis of homeland security issues. MITRE Corp. operates the Homeland Security Systems Engineering and Development Institute (HSSEDI) as an FFRDC for DHS under contract 70RSAT20D00000001.

The HSSEDI FFRDC provides the government with the necessary systems engineering and development expertise to conduct complex acquisition planning and development; concept exploration, experimentation and evaluation; information technology, communications and cyber security processes, standards, methodologies and protocols; systems architecture and integration; quality and performance review, best practices and performance measures and metrics; and, independent test and evaluation activities. The HSSEDI FFRDC also works with and supports other federal, state, local, tribal, public, and private sector organizations that make up the homeland security enterprise. The HSSEDI FFRDC’s research is undertaken by mutual consent with DHS and is organized as a set of discrete tasks. This report presents the results of research and analysis conducted under Task Order 70RSAT23FR0000067: 5G-Advanced/XG Gaps Assessments and Mitigations for DHS.

The purpose of the task is to identify 5G-Advanced and 6G capabilities that pose the greatest opportunities and threats to DHS, and engage industry and standards bodies to guide industry toward deploying solutions that meet DHS needs.

The results presented in this report do not necessarily reflect official DHS opinion or policy.

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