SIDELINK OPTIMIZATIONS FOR LAYER-3-BASED IoT RELAYING IN 5G NR

Subin Narayanan, Olof Liberg, Andreas Höglund, Dimitris Tsolkas, Nikos Passas, and Lazaros Merakos

ABSTRACT

The effective support of 5G-IoT requires cellular service in deep coverage areas while providing long battery life for IoT devices that perform infrequent small data transmission toward the base station. Relaying is a promising solution to extend the coverage while at the same time meeting the battery life requirements of IoT devices. Considering this, we analyze the suitability of layer-3 relaying over the 3GPP Release 16 NR-PC5 interface to support massive IoT applications. More precisely, we study the unicast connection establishment mechanism over the NR PC5 interface in a partial coverage scenario. Further, a set of optimizations on the Release 16 NR-PC5 procedure to effectively support massive IoT applications are proposed and analyzed. The obtained performance evaluation results, which are presented in terms of data success probability, device power consumption, and signaling overhead, quantify how effectively the Release 16 NR-PC5 interface can support the requirement of IoT in the 5G and beyond era. The proposed sidelink small data transmission and frame-level access provides the largest gain overall and can reduce the device power consumption by an average of 68 percent and signaling overhead by 15 percent while maintaining a data success probability of more than 90 percent in an IMT-2020 defined IoT traffic scenario.

INTRODUCTION

The Internet of Things (IoT) manifests the vision of wirelessly interconnecting all electronic devices that can potentially benefit from being connected. The number of such devices is increasing exponentially, and Ericsson estimates that there will be roughly 26.4 billion connected devices by 2026 [1]. The cellular network is one of the key enablers for this exponential growth. The accelerated growth in IoT technologies is driven by the introduction of IoT-specific technologies by the 3rd Generation Partnership Project (3GPP) from Release 13, known as cellular IoT (CIoT) technologies [2]. In general, CIoT technologies are designed to connect large volumes of battery-powered devices of low mobility while also being able to operate in deep coverage areas (hard to reach) and performing infrequent small data transmissions toward the base station [3].

Due to the longevity of IoT devices, the currently available CIoT technologies, such as NB-IoT and LTE-M, are expected to provide their services in the 5G era too. Considering this, in the 5G New Radio (NR), a new class of devices called reduced capability (RedCap) NR devices has been introduced, which targets IoT use cases that do not overlap with those covered by NB-IoT and LTE-M [4]. For the support of massive RedCap devices, relaying is a relevant auxiliary feature that can assist by providing coverage enhancements, reduced energy consumption, improved robustness, as well as higher capacity.

In a relaying network, a relay node is placed in between an IoT device that is in deep coverage, referred to as a remote user equipment (UE), and the base station. The relay node forwards signaling and data from the remote UE to the base station, and vice versa. The relay process can be classified based on various criteria, such as the operational layer in which relaying is implemented and the type of node that performs the relaying. Considering the classification based on operational layers, three types of relays are defined: layer-1, layer-2, and layer-3 relay, one-to-one mapped to the protocol layer where the relaying functionality is implemented [5–7]. Based on the type of the relay node, two types of relaying mechanisms are defined: UE-based and network-based relaying [6, 7].

In 5G NR, integrated access and backhaul (IAB) is specified as a layer-2-based relaying technology for enhanced mobile broadband (eMBB) applications. Being a layer-2 relay, any optimizations on the IAB node to support IoT use cases will impact the existing cellular architecture. In this article, we focus on layer-3 UE-based relaying since it has the minimum impact on the radio protocol stack (existing non-5G networks can support it) and exploits the potential to expand the coverage in a more dynamic and flexible way using UEs as relays. To this end, we consider the recent 3GPP study of the NR-sidelink (NR-SL) relay as part of the ongoing Release 17 activities [7, 8]. The 3GPP studies target both layer-2 and layer-3 UE-based relaying architectures; however, since a new protocol layer called the adaptation layer is required (implemented above the RLC layer as depicted in Fig. 1) in a layer-2 relay architecture, we focus on the more backward-compatible layer-3 architecture [5–7]. In the layer-3 architecture, the minimum impact on the existing radio protocol stack is achieved, as the relaying function is implemented over the application layer of the relay node (relay UE); thus, there is no need to introduce new signaling between the base station and relay UE. The interface between two UEs that supports the sidelink communication is referred to as PC5. The Release 16 NR-PC5 is designed for broadband applications. Considering this, the main contributions of this article are the following:

• A comprehensive study on the layer-3 architecture over the NR-PC5 in a partial coverage scenario
• A set of optimizations to support IoT application over the Rel.16 NR-PC5, accompanied with performance evaluations that quantify the gains of the proposed optimizations

The rest of the article is organized as follows. The next section presents the layer-3 architecture for UE-based relay over the NR-PC5 interface. A description of the unicast connection establishment procedure of NR-PC5 and our proposed optimizations in the unicast connection establishment to support IoT applications over the NR-PC5 interface are presented following that. We then compare the performance of the proposed optimizations. Conclusions and insights are included in the final section.
Relaying Architecture

In the partial coverage scenario, the remote UE is located outside the coverage of the base station, whereas the relay UE is located within the coverage of the base station. The architecture of a UE-based single-hop relay with layer-3 architecture in a partial coverage scenario is depicted in Fig. 1 [7]. The interface between a UE and the base station is referred to as the Uu interface.

In the architecture, in both the user plane and the control plane, the packet flow is performed through the network or from the remote UE to the relay UE via the PC5 interface. This is crucial for ensuring the reliability and security of the communication. The architecture includes higher-layer functionalities such as ciphering and integrity protection. After the higher-layer functionalities are performed, the packet is re-encoded and re-modulated. The demodulation and decoding of the received packet implies that the relay process can adapt to different channel conditions which the two communicating sides may experience. This is achieved by the Uu link, the base station, and the relay UE.

The remote UE initiates the procedure by sending the discover signal, called the direct communication request (DCR). The remote UE keeps on sensing the channel based on the resource sensing performed, and the reservation information (SCI) is sent. After receiving the DCR, the relay UE initiates the authentication and security command procedure described in [7, 10]. When the relay UE receives the packets, the relay UE decodes and demodulates the packet, and passes it to the higher layers to perform other functions such as ciphering and integrity protection. After the higher-layer functionalities are performed, the packet is re-encoded and re-modulated. The demodulation and decoding of the received packet implies that the relay process can adapt to different channel conditions which the two communicating sides may experience. Therefore, the Uu link, the base station, and the relay UE can be considered as part of the overall communication architecture.

Unicast Connection Establishment

Figure 2 depicts the unicast connection establishment procedure in NR-SL [13, 14]. Our study focuses on the uplink transmission in the unicast connection establishment. A description of the signaling flow is given below.

The remote UE initiates the procedure by sending the discovery signal, called direct communication request (DCR), over the physical sidelink shared channel (PSSCH). The DCR message from the remote UE contains a service identifier of the service for which the remote UE is communicating with the relay UE. The application ID (an identifier for a UE within a particular application) of the relay UE is mapped to the layer-2 ID of the relay UE. After receiving the DCR, the relay UE initiates the authentication and security command procedure to mutually authenticate the connection with the remote UE. Once the UEs are authenticated, direct link security mode control is initiated by the remote UE by sending a direct link security mode command to the remote UE. If the remote UE accepts the direct link security mode command, the remote UE will respond to the relay UE by sending a direct link security mode complete message. After the successful security mode control, keys and security algorithms are used to protect integrity and cipher all SL data communicated between the remote UE and the relay UE. The direct link security mode control, the relay UE will send a direct communication accept (DCA) message to the remote UE, and a successful DCA transmission allows the unicast data transmission between the remote UE and the relay UE. After the data transfer, the communicating UEs can either keep the unicast link alive or release the link; accordingly, there are two signaling mechanisms.

Connection Release: The connection release procedure is performed to release the existing PC5 unicast link between the remote UE and relay UE. After receiving the direct link release request, the remote UE will stop the ongoing communication over the given PC5 link and then respond to the remote UE with a direct link release accept message.

Connection Alive: The connection alive procedure is performed to keep the PC5 unicast link between the remote UE and relay UE alive. After the successful transmission of direct link keep-alive request and response, the PC5 link identifier is stored in both the relay and remote UEs for a duration specified by a connection alive timer value. This stored PC5 link identifier allows us to skip the direct link authentication and the direct link security mode command procedure in the subsequent periods.

In the NR-SL, when the remote UE sends a signaling message, it also reserves a resource for its next transmission. Based on the resource sensing performed, and the reservation information is included in the first stage sidelink control information (SCI). The remote UE keeps on sensing the channel until the slot where its future resources are reserved to check if any other remote UE with higher priority has reserved the same resources. If the remote UE detects a higher priority reservation from a peer remote UE, the remote UE releases the reserved connection with the relay UE for the first time), the service identifier is mapped to the layer-2 ID of the relay UE.

After receiving the DCR, the relay UE initiates the authentication procedure to mutually authenticate the connection with the remote UE. This is realized by a direct link authentication request sent by the relay UE, followed by an authentication response message from the remote UE.

Once the UEs are authenticated, direct link security mode control is initiated by the remote UE by sending a direct link security mode command to the remote UE. If the remote UE accepts the direct link security mode command, the remote UE will respond to the relay UE by sending a direct link security mode complete message. After the successful security mode control, keys and security algorithms are used to protect integrity and cipher all SL data communicated between the remote UE and the relay UE. The direct link security mode control, the relay UE will send a direct communication accept (DCA) message to the remote UE, and a successful DCA transmission allows the unicast data transmission between the remote UE and the relay UE. After the data transfer, the communicating UEs can either keep the unicast link alive or release the link; accordingly, there are two signaling mechanisms.

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resources and restarts the connection establishment procedure from the point at which the collision happened.

**OPTIMIZATIONS FOR iOT RELAYING**

The 3GPP Release 16 NR-SL is originally designed for the vehicle-to-everything (V2X) application and hence is designed to support high data rate, low-latency applications. The Release 16 NR-SL follows a sensing-based resource allocation method when working in an out-of-coverage area. The sensing-based approach requires the remote UE to be in on-state for a duration of sensing window of 1000 ms to detect the SL transmissions from the peer UEs. Since the sensing is not energy-efficient, the sensing-based approach can be for IoT UEs as these are usually battery-operated. Moreover, the ProSe and V2X applications are connection-based, and hence the NR-SL may not be optimal for IoT, which is more message-based. Hence, in this section, we present a set of optimizations on the 3GPP Release 16 NR-SL to support IoT relaying applications.

**PRIORITY INFORMATION ASSISTED RESOURCE RESERVATION FOR COLLISION REDUCTION**

In the 3GPP Release 16 NR-SL, a two-stage SCI principle is used for data/signaling transmission [7, 13, 14]. The first stage SCI contains information on PSSCH resources, the priority of the transmission (priority values are estimated based on quality of service, QoS), and future PSSCH reservation (the first SCI can be decoded by any peer UE in the proximity for channel sending purpose). The second stage SCI contains the remaining scheduling information of the PSSCH (e.g., MCS, UE-specific DMRS) to assist the destination UE to decode the PSSCH. Now consider the scenario where two or more remote UEs are transmitting in a slot with different resources (subchannels), and they reserve the same subchannel for future transmission. In this scenario, the reserved future transmissions from these remote UEs are considered as collided. To avoid this collision, we propose that for the NR-SL relay, the relay UE decides on which remote UE is allowed to transmit its next packets in the reserved subchannels based on the priority value (the relay UE selects the remote UE with the highest priority value) included in the first stage SCI. The relay UE can convey this information to the remote UEs (which transmitted the packet and reservation information toward the relay UE) over the physical sidelink feedback channel (PSFCH). To realize this procedure, the 3GPP Release 16 defined PSFCH channel needs to be modified to convey the information from relay UE to remote UEs.

**CONTENTION-BASED CONNECTION ESTABLISHMENT**

In this proposal, all the signaling and data exchange in the connection establishment procedure are contention-based. We propose that in a slot, all the remote UEs for any of their transmissions, namely the direct communication request, the security response, the authentication response, and the data transmission, randomly select a subchannel from the pre-configured set of subchannels (resources). In contention-based access, the remote UEs do not perform channel sensing; hence, the two-stage SCI principle is omitted, and information on the priority of transmission, future resource reservation, and all the scheduling information of the PSSCH are included in a single-stage SCI. Also, the remote UEs are awake only when they have a packet to transmit, and the rest of the time they stay in the idle state. This procedure is different from 3GPP Release 16 NR-SL, where the remote UEs have to be in the receiving state to sense the resource occupation by the peer remote UEs. The benefit of the approach is the reduced energy consumption, and the drawback is the increased risk of collision. However, in IoT applications, the stationarity of the remote UE devices and the long transmission period minimize this risk.

**FRAME-LEVEL-BASED ACCESS**

In this approach, we propose that the relay UE performs the channel sensing on behalf of the remote UE and conveys the sensed information to the remote UE. For this purpose, we propose a new time window called SL Frame, which consists of a number N of continuous slots. At the beginning slot of each SL frame, the relay node broadcasts the available information on unoccupied resources in the ongoing SL frame, and the remote UE monitors this broadcast information. For example, if a remote UE has chosen an SL frame for its DCR transmission, at the very first slot of this SL frame, the remote UE listens to the broadcast information from the relay UE mentioning the unoccupied resources in the SL frame. Based on this information on the unoccupied resources in the SL frame, the remote UE can randomly choose a resource for its DCR transmission from a set of unoccupied resources in the SL frame.

The advantage of this approach is that the remote UE needs to monitor only the first slot of the SL frame which it has selected for the DCR transmission, and hence energy consumption is reduced. If two or more remote UEs choose the same subchannel for the DCR transmission, the transmission is considered as collided, and the collided UE performs the backoff mechanism and retransmits the DCR. If the DCR transmission is successful, the remote UE reserves the resource for future transmission with a constant offset. That is, the remote UE reserves a resource for its future transmission in the same slot in the next SL frame and subchannel at which current transmission is being carried out. If the current transmission from a remote UE is successful, most likely future transmission will also be successful. This is because the current transmission is successful only when no other remote UE has chosen the resource chosen by the transmitting remote UE. Then the transmitting remote UE chooses the same frequency resource in the next SL window for its future transmission and informs the relay UE so that it knows about this reservation. The relay UE broadcasts this information at the beginning of the next SL window to all other remote UEs that plan to transmit the DCR. Hence, the remote UEs in the next SL window will exclude the reserved resources for their DCR transmission. We assume that the remote UE receives this feedback from the relay UE before the end of the ongoing SL frame in which the current transmission is occurring. The drawback of the approach is the increased risk of collision compared to the legacy sensing-based approach as the granularity of sensing is SL frame length instead of one slot.

**SMALL DATA TRANSMISSION**

Considering the low data rate transmission of IoT applications,
the Release 16 NR-PC5 process can be modified by bundling the DCR, data packet, and keep the link alive requests, and send all together in a single transmission. In this method, the remote UE follows the frame-level access mechanism to select the resources. Compared to legacy unicast establishment (with connection alive) shown in Fig. 2, instead of nine signaling exchanges between the remote UE and the relay UE, there will be only two signaling exchanges, as shown in Fig. 3. The procedure is as follows:

- In the very first period, the connection establishment procedure follows the same signaling flow as depicted in Fig. 2, with a request to keep the link alive between the relay UE and the remote UE. In the first period, we cannot bundle all the SL messages in a single transmission as the remote UE does not have a security setup with the relay UE. In this step, the resources are selected following the frame-level access mechanism.

- If a remote UE has successfully transmitted the keep the link alive message in the first period, in the second period the remote UE transmits the DCR, data packet, and a keep-alive request (for the next period) following contention-based access, using the saved PC5 link identifier. This procedure continues for the next periods as well in the case when contention-based access is successful. The small-data-based connection establishment procedure is shown in Fig. 3. All the red lines in Fig. 3 can be removed when the link is kept alive.

Mostly, the remote UEs are stationary to a much greater extent than V2X UEs, which further motivates this improvement. In the approach, the number of signaling exchanges is reduced, which further reduces the probability of collision and energy consumption of remote UEs. The advantage is that the transmission spans more resources since data and signaling are bundled together in a single transmission.

**Performance Evaluation**

For the performance evaluation study, we considered evaluation parameters around those proposed by IMT-2020 [14], as listed below:

- At least 10th remote UEs/km² are supported.
- Each of 10,000 households in a densely populated city center is equipped with a relay and contains 100 connected devices.
- The target household refers to one interference-isolated relay network.
- Each remote UE creates packets of size $V$ of 208 bytes.
- The packet inter-arrival time (IAT) belongs to the interval between 1 s and 10 s.

We compare the performance of the proposed optimizations against the baseline system (without the optimizations) under the worst case scenario; that is, we assume that when two or more transmissions use the same resource unit, there is certainly a collision, and thus the transmissions are considered failed. In this work, we used MATLAB-based simulations for performance evaluation, and considered the randomness in the device distribution, resource selection, resource reservation, and retransmissions [3].

For our study, we assume an SL carrier width of 5 MHz, with 15 kHz of subcarrier spacing, which leads to 25 resource blocks (RBs) over the carrier width. The NR-SL defines a subchannel as a group of RBs in the same sub-frame. A subchannel is the smallest resource allocation unit in the domain frequency. Within the 5 MHz bandwidth, we consider that there are 2 subchannels available, each with 10 RBs. The remaining 5 RBs are added to the second subchannel, with the condition that these additional RBs are not used for transport block size (TBS) determination [15].

We define the data success probability as the ratio of the total number of remote UEs that successfully transmitted the unicast data to the total number of remote UEs which attempt to transmit the unicast data. As shown in Fig. 4, the data success probability is highest for the sensing-based approaches (Release 16 baseline scheme and PSFCH feedback on resource reservation) and lowest for the contention-based approach at a low value of IAT. This is because the output of the sensing procedure followed by the remote UEs before sending a packet is a set of resources that are unreserved by other remote UEs in the system, and hence the collision in the SL packet transmission is lowest compared to the other schemes. Also, we can observe from Fig. 4 that relay assistance through the feedback channel in the sensing scheme offers a very small gain compared to the baseline scheme.

In contention-based access, all the signaling and data exchange are contention-oriented, and therefore the collision probability will be higher. Since the update on the unoccupied resources in the system is available per SL frame for the frame-level access and for the sensing-based approach, and updates on unoccupied resources are available in each slot, the data success probability of the sensing-based approach is better than that of the frame-level access. Furthermore, as we can observe from Fig. 4, the small data transmission has a lower success probability than the sensing-based scheme and frame-level access. This is because small data transmission from a single remote IoT device spans two subchannels (since data, DCR, and alive requests are bundled and send together); hence, probability collision increases in the random selection of resources.

The intended benefit of the IoT optimizations is not to increase the success probability, but rather maintain it while the remote UE energy consumption is reduced. Figure 5 shows the normalized UE energy consumption, where the energy consumption of every scheme is normalized based on the highest energy-consuming scheme. We can observe that UE energy consumption is highest for the sensing-based method. This is because in the sensing-based method, the remote UE is always in the receiving state, listening to the first stage SCI broadcast by the other remote UEs. For contention-based access, the UE energy consumption is high at a low value of IAT (i.e., at high load). This is because high retransmissions, due to an increased number of collisions, increase the energy consumption at a low value of IAT. At a high value of IAT, collisions are reduced, and hence the remote UE energy consumption is very low, as the remote UE is awake only when it is transmitting, and no
energy-consuming channel sensing is required. For the frame-level-based access with a constant offset, the remote UEs are awake only when the remote UE is transmitting, and also at the first slot of the frame in which it has scheduled its transmission. Due to this approach, as we can see from Fig. 5, the frame-level access with constant offset has very low UE energy consumption. Similarly, for small data transmission, the UE energy consumption is low, as the UE is only awake when it is transmitting the DCR together with data and keep-the-link alive message are all together in a single transmission with a single stage of the transmission. Also, the direct communication accept message is not sent from the relay UE to the remote UE in the small data transmission.

CONCLUSION

3GPP Release 16 NR-SL can be used to enable layer-3-based UE relaying. Further, the existing NR-SL procedure for connection establishment can be optimized for IoT layer-3 relaying. Being a layer-3 relaying solution, these optimizations on the SL interface would not have an impact on the existing Uu specification.

The goal of optimization was to maintain roughly the same success probability while the energy consumption and signaling overhead are reduced compared to the Release 16 sensing-based baseline approach. Our performance evaluation shows that the frame-level access solution and small data transmission solution are the best options for layer-3-based UE relaying for IoT applications. These maintain the data success probability on essentially the same level as the Release 16 NR-SL baseline approach, while at the same time reducing the remote UE energy consumption by up to 68 percent and signaling overhead by 15 percent. In future work, we aim to study the sidelink relay considering non-ideal channel conditions.

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