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Dynamic Link Selection Method for Suitable Communication Cost Allocation in Internet of Vehicles

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Abstract

As connected cars become widespread, the range of users who rely on vehicle communication—passengers, manufacturers, and service providers—has diversified. Alongside conventional single-line communication provided by car manufacturers, new possibilities for leveraging multiple communication links, such as passengers' smartphones, have emerged. To encourage effective use of these multiple communication links, it is essential to fairly allocate communication costs between those who bear them and those who benefit. To address this issue, we propose a dynamic communication link selection method that identifies beneficiaries in real time and considers cost factors. Specifically, our approach achieves adaptive link selection by accounting for subscriber or cost-bearer's information and cumulative data usage. In a future Internet of Vehicles environment that integrates diverse communication links, we show that the proposed method can appropriately select links for applications based on each link's status or statistics and its associated cost-bearers.

Keywords:

Internet of Vehicles, Multipath Communication, 5G Core

1. Introduction

The connected car, equipped with communication functions, is becoming increasingly popular. Connected cars provide passengers with connected services such as a remote key, navigation, and remote control over network. "Internet of Vehicles (IoV)" refers to the entire system, including the cloud facilities communicating with the connected car and providing connected services.

The communication function of a connected car is generally introduced at the time of manufacture, and the vehicle manufacturer bears the communication cost as the primary bearer; the manufacturer installs a communication device such as a cellular mobile router and a SIM card with a network service contract. This form of installation is a result of the mandatory equipment of automatic emergency call systems (eCall) in Europe, which requires the installation of communication functions at the time of vehicle shipment and vehicle manufacturers' efforts to accommodate connected services in a single communication link to reduce communication cost at the emergence era of connected services.

In the future, the spread of 5G will lead to the emergence of advanced connected services and further increase communication demands by various beneficiaries, the users of the connected services. In addition to the demand by manufactures, such as data collection of various vehicle information to the cloud for advanced connected services like high-precision maps and traffic digital twins, the communication needs of passengers and other service providers will also increase. For example, passengers demand high-capacity communication to enjoy video streaming for in-car entertainment systems. The third-party service providers utilize various vehicle information to provide services, telematics car insurance, for example.

Using multiple communication links together is expected to ensure the stable provision of such advanced connected services. For example, when a single cellular network can not provide enough coverage, utilizing multiple cellular mobile services would achieve bypass and increased bandwidth. Even when traveling outside of coverage, when a large-scale failure occurs at a cellular mobile network, or when a natural disaster damages network facilities, it is possible to increase the availability of urgent and high-priority communications, such as operator calls to request rescue. It can also improve communication quality by combining the available bandwidth of multiple communication links for large-volume communications such as video stream viewing.

The introduction of multiple communication links in vehicles can take two forms: (1) vehicle manufacturers install multiple communication devices and contracts (SIMs), or (2) passengers and third-party service providers bring and install their communication links, and the vehicle utilize them together with the one installed by the vehicle manufacturer. In this study, we focus on the second case. In addition to the communication link contracted by the vehicle manufacturer, the vehicle accommodates and/or manages communication links provided from other parties; tethering connections of passengers' smartphones and communication devices installed by third-party service providers. The traditional way of installing communication functions has three major deficiencies: passengers and vehicle owners cannot freely change the configuration, are limited to the communication technology at the time of manufacture, and may suffer disadvantages due to the shutdown of old communication services (sunset). Suppose vehicles can adaptively utilize communication devices such as a tethering connection. In that case, the devices directly facing the cellular mobile network are the passenger's smartphones, which have the advantage of cost optimization through more flexibility in network service contracts and the ability to follow the latest communication technology due to the ease of replacing communication devices.

On the other hand, the current situation in which communications of different beneficiaries coexist on a single communication link provided by the vehicle manufacturer will change to a form in which communications of multiple beneficiaries coexist on the communication links of multiple different subscribers and cost-bearers. Only regulated communication link use that satisfies the cost-bearers will ensure the flexible use of multiple communication links. Therefore, in the future IoV, where vehicles utilize multiple communication links flexibly together, should have a mechanism to distribute the cost burden appropriately to the communication beneficiaries.

This study proposes a method for dynamically selecting communication links for each application based on the assumption that cost-bearers (subscribers of the network) and beneficiaries (users of applications that send and receive data) of each line are known. These three functions ensure the use of communication links intended by the cost-bearers and appropriate cost distribution to the beneficiaries.

1. Selecting communication links based on cost-bearers and beneficiaries
2. Recording a trace when a beneficiary uses a communication link that it did not subscribe to
3. Authorizing other beneficiaries to use a link up to the limit set by the cost-bearer

This paper is organized as follows. In section 2, we describe our previous work, which are the premise of the proposed method. In section 3, we summarize the related works of the proposed method. In section 4, we describe the implementation of the communication link selection function (defined as Link Selector) that implements the proposed method. In section 5, we evaluate the feasibility of the proposed method through experiments. Finally, conclusions and future issues are summarized.

2. Our Previous Work

Toyota Motor Corporation is studying the feasibility of a communication function that does not assume the vehicle manufacturer's installation of a communication device at the time of production, in order to expand the freedom of network service choice for passengers, owners, and third-party service providers (3rd vendors) of connected cars. This paper is built on this previous work.

In our preceding research, the connected car is equipped with a mechanism that allows the vehicle manufacturer, passengers, owner, and third-party vendors to add communication links and contracts freely, even after the vehicle is shipped. Simultaneously, it is essential to ensure communication security and manage the communication links provided to the vehicle. In our method, the vehicle manufacturer operates the 5G core (5GC), which can now be operated on a cloud-based basis, and the 5GC utilizes Non-3GPP Interworking Function (N3IWF) to centrally manage internet access through any network in a secure manner.

The connected car in our method is equipped with a SIM, which is used to authenticate to the 5GC, independent of the cellular contract. Once the 5GC accommodates the vehicle, the operator can centrally manage the vehicle's communication with functions equivalent to an MNO's. For example, the Authentication Server Function (AUSF) can provide SIM-based user authentication, and the Charging Function (CHF) can manage communication usage on each Non-3GPP Interworking User Equipment (N3IWUE). The system is called "IRIGATE," where the connected cars and the 5GC achieve loose coupling between the vehicle, communication devices, and communication contracts. The IRIGATE can provide communication users with the secondary benefits of avoiding the risk of communication outages due to carrier sunset as described in section 1 and of communication cost at a bit rate appropriate for the times.

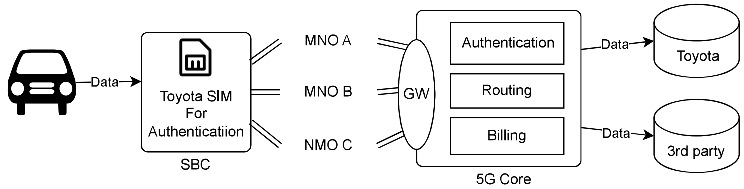

Figure 1. IRIGATE system overview

Figure 1 shows the system configuration of IRIGATE. The IRIGATE consists of a 5GC in the cloud and an in-vehicle communication device. The in-vehicle communication device is connected to another communication device, such as a passenger's smartphone with tethering enabled or mobile routers installed independently by a third vendor via Ethernet, Wi-Fi, or USB interface. The in-vehicle communication device runs N3IW-UE on each communication link to establish a secure communication path with the 5GC. In our previous work, we implemented an in-vehicle communication device using a Linux-based single-board computer (SBC) with Ethernet, USB, and Wi-Fi interfaces, a CAN interface for vehicle information collection, and a SIM slot. We built the IRIGATE experiment environment using a free5GC-based core on AWS.

3. Related Works

Studies have been actively conducted to use multiple communication links together in an automotive environment in order to improve communication quality and availability, including multipath communication protocols such as Multipath TCP [5] and MPQUIC [6], or SDN [7] and SD-WAN-based method [8]. There are studies that evaluate multipath communication technologies in mobile environments [9,10]. As in the literature, our study proposes introducing multipath communication technology in a vehicular mobile environment. In addition, we assume that each communication link provided to the vehicle has different contractors and cost-bearers for each, and the communication control must consider combining communication links and each application on top of it in an appropriate manner, as in the SD-WAN system.

In our study, we implement the mechanism for aggregating the multiple communication links using a 5GC, as described in the previous study in Section 2. The 3GPP defines ATSSS (Access Traffic Steering, Switching, and Splitting) [11], which can use MPTCP and MPQUIC as underlay protocols. Our research utilizes multipath communication between 5GC and UE as ATSSS does. ATSSS defines the control of application communication based on the QoS Flow Identifier (QFI). In contrast, our method selects and distributes the application traffic over multiple communication links based on the consensus among the application beneficiaries and the cost-bearers of each communication link. While our work parallels ATSSS, it is possible to introduce the communication link selection method proposed in our study into the ATSSS specification.

4. Proposed method: dynamic link selection for application communication

In this chapter, we propose a method of communication link selection for each application over multiple communication links, considering the cost-bearers of each communication link and the beneficiaries of each application communication.

4.1. Requirements for communication control in a vehicle equipped with multiple links

The following is a list of functions required for communication control in a connected car equipped with multiple communication lines.

- Identification of application communication, identification of communication link
- Selecting a communication link for each application communication
- Dynamically changing communication link selection for application communication based on conditions
- Measuring and limiting the amount of data for each communication link by the application

4.2. Communication control by Link Selector

To realize the requirements, we design a communication link selection function, namely “Link Selector,” which identifies the communication links as “Link” and each application traffic as “Flow” and controls the combination of flows and links based on “Policy.” The Link Selector is deployed in both the vehicle and the cloud to control communication link selection on behalf of the application. The Link Selector comprises a controller and agents; the controller resides in the cloud, and the agent runs in the vehicle to manage and control the bi-directional link selection.

The Link Selector identifies the communication of each application as "flow" based on the 5-tuple information of packets and IP ToS. For example, the video stream of in-vehicle entertainment for passengers and the CAN data upload communication by the car manufacturer are identified as individual flows. The system assumes that each flow uniquely identifies an application and its user, the beneficiary.

The Link Selector identifies the communication links provided to the vehicle as "link" and assigns a unique ID. For example, a cellular mobile communication link provided by a car manufacturer, a tethering connection of a passenger's smartphone, and a cellular mobile router installed by a third vendor are treated as different communication links. The system assumes that each link has its cost-bearer and can be uniquely identified.

The Link Selector manages the rules and methods for sending and receiving communications for a specific flow on a specific link as "policy." Policies comprise static and dynamic policies. The static policies specify a set of links for communication of a specific flow, while the dynamic policies define dynamic link selection depending on link status and quality. For example, a static policy states that CAN data flow is uploaded through the vehicle manufacturer's communication link, while the flow of in-vehicle entertainment video streams is downloaded through the passenger's own cellular communication link.

The Link Selector performs periodic E2E communication checks between the agent and controller over each communication link, shares statistics, and synchronizes policies from the controller to the agent. The communication check measures the RTT between the controller and the agent. Also, it serves as a keep-alive communication to maintain the NAPT session and outer IP address of the middlebox. The Link Selector controller has a mechanism to manage and change the policy of the vehicle-side agent. The Link Selector controller enables dynamic policy changes based on requests from cost-bearers, application users, and IoV operators.

The Link Selector controller periodically queries the CHF for the amount of data flowing to the UPF via each N3IWF and uses the obtained statistics to control each application's data volume for each communication link. For example, the system monitors the upper limit of the communication volume until the end of the month for a specific link based on the current accumulated data volume. In this system, we assumed that the correspondence between NWu and vehicle-side links is predefined, and that other systems would input the data volume specifications and permissions.

4.3. Implementation

We implement the Link Selector using the Multipath UDP Proxy (MUP) from the literature [12]. The flow and link in Link Selector correspond to the flow and path concepts in MUP.

```
1  [[service]]
2  bind_addr = "0.0.0.0"
3  port = 10000
4  flow_id = 10000
5
6  [commands]
7  init="""
8  group 10 create
9  group 10 add path 0
10 group 10 add path 1
11 group 10 set policy active_standby
12 group 10 set active path 0 preempt
13 flow 10000 set group 10
14 """
```

Figure 2. Example of policy for Link Selector Agent

We extend the RTT measurement and statistics-sharing mechanism of MUP to implement policy synchronization between Link Selector controller and agents. Figure 2 shows an example of a policy description for a MUP client. In this policy, communication received by the MUP client on UDP port 10000 (lines 2 and 3) is treated as flow 10000 (line 4), path 0 is the primary link, and path 1 is the standby link (lines 11 and 12), which is switched according to the path status.

The Link Selector agent is placed between the application client and the N3IW-UE on the vehicle side, and the Link Selector controller is connected to the UPF of the 5GC. On the vehicle side, the Link Selector agent, acting as a forward proxy for upload traffic, accepts the application client's communication. On the 5GC side, the Link Selector controller, acting as a reverse proxy, communicates with the application server on behalf of the application client.

Our implementation replaces cooperation between the Link Selector and the CHF with an external program that queries communication statistics to the MUP server via API and modifies the policy. The program manages the data volume limit for an application on each link; if the limit has been reached, it reflects the policy of turning off the usage of the link from the application.

5. Evaluation

In this section, we introduce the Link Selector into the IRIGATE environment described in section 2 to verify the feasibility of the link selection method for each application communication.

5.1. Evaluation environment

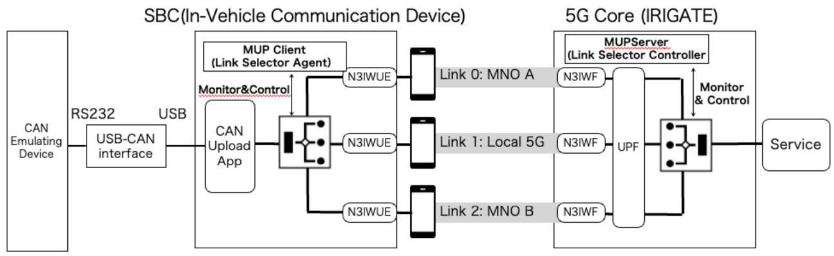

Figure 3. Experiment Environment

Link ID	Path ID in MUP	Link Type	Cost-Bearer
0	0	Public 4G of MNO A	Passenger
1	1	Local 5G	OEM Manufacturer
2	2	Public 4G of MNO B	3rd vendor

Table 1. Communication lines in our experiment

Figure 3 shows the experimental setup. The environment follows the IRIGATE environment described in section 2, and the SBC is assumed to be connected to communication links, as shown in Table 1. The communication links comprise a USB tethering-enabled vehicle passenger's smartphone, a Network Access Device (NAD) installed by the car manufacturer, and a mobile router installed by a service provider for telematics insurance.

In the experiment, to emulate changes in the communication environment due to movement, we operate a Local 5G link (path1) base station in an anechoic chamber to reproduce movement in and out of the coverage area. The SBC receives CAN data from the CAN I/F and uploads it to the cloud server. CAN data uploading is a vehicle information collection application in which the vehicle manufacturer is the beneficiary. It consists of two channels: high priority (1ch) and low priority (2ch). The high-priority CAN requires highly available transmissions. Each CAN data communication is a text data transmission using UDP, with a bit rate of about 10 to 40 kbps.

5.2. Evaluation scenarios

In this experiment, we confirm that our method can properly select links for each two CAN data uploads in the following three scenarios.

- Scenario 1: CAN data uploads are performed via the car manufacturer's link (path1). And when path1 is out of service, only the high-priority CAN 1ch is diverted via the passenger-provided link (path0).
- Scenario 2: CAN data are uploaded via path1. And when path1 is disconnected, only CAN 1ch will go through the third vendor's link (path2)
- Scenario 3: CAN 1ch transmits on path0 with the passenger's permission, and CAN 2ch transmits on path1. CAN 1ch transmits via path1 after the data usage on path0 reaches the 100KB upper limit.

In test scenarios 1 and 2, we verify the ability to dynamically switch to a link other than path1, assuming that the vehicle manufacturer who is the beneficiary of the CAN data upload is given permission from each cost-bearer to utilize the respective links. Between test scenarios 1 and 2, we perform an update of the policy from the Link Selector controller to the agent to confirm that the diverted link is changed between the two scenario. In test scenario 3, we confirm that the link is switched based on the authorized data volume. In each test scenario, we visualize the received throughput of the Link Selector controller for each link and each flow basis to clarify which link each CAN data is uploaded. In test scenario 3, we visualize the amount of data received on each link of the controller for each flow in order to confirm the amount of data usage.

5.3. Evaluation results: scenario 1

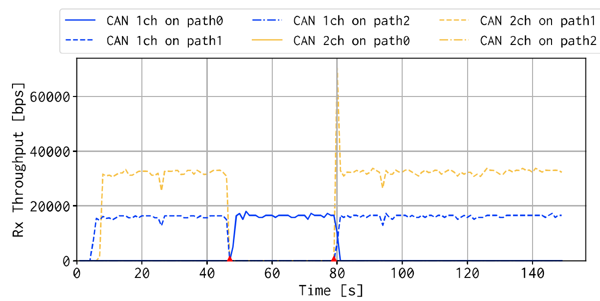

Figure 4. Scenario 1: Rx throughput of CAN 1/2ch on each link

Figure 4 shows the received throughput of CAN data on each link. We turn the base station of path1 off at 47s and bring it back at 79s. The traffic of CAN 1ch switches from path1 to path0 in the 47s and returns to path1 in the 79s, continuously performing its upload. CAN 2ch uses only path1, and upload is disturbed when out of coverage.

From this experiment, we can confirm that the proposed method allows link selection for each application: the upload of CAN 1ch dynamically switches between path1 and path0 based on the state of communication links, while the upload of CAN 2ch uses only path1 statically.

In this implementation, dynamic link switching depends on a one-second cycle of RTT measurements between the agent and the controller. This disrupts upload up to one second; packets sent during link switching are lost because the nature of UDP. Early detection of link disconnections and loss reduction is possible by implementing retransmission, using supported protocols, and collaborating with the intermediate cellular mobile terminal device.

5.4. Evaluation results: scenario 2

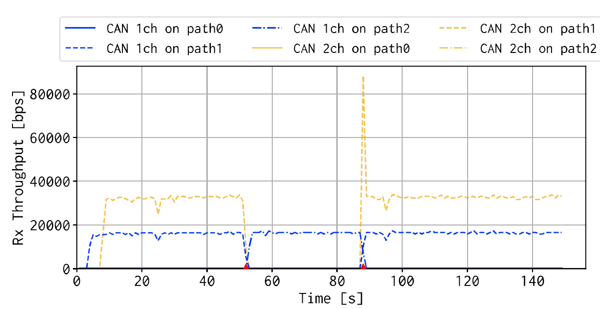

Figure 5. Scenario 2: Rx throughput of CAN 1/2ch on each link

Figure 5 shows the received throughput of CAN data on each link. We turn the base station of path1 off at 52s and bring it back at 88s. The traffic of CAN 1ch switches from path1 to path2 in the 52s and returns to path1 in the 88s. CAN 2ch upload uses only path1, and traffic is disturbed when out of coverage.

In test scenario 2, unlike test scenario 1, the fallback destination for CAN 1ch is path2. This policy change was employed prior to test scenario 2, and this experiment confirms that the Link Selector agent reflects the intended policy and achieved appropriate link selection.

5.5. Evaluation results: scenario 3

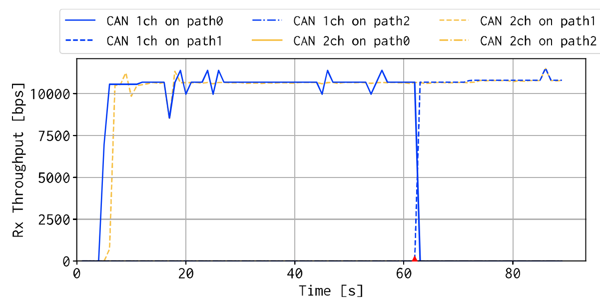

Figure 6. Scenario 3: Rx throughput of CAN 1/2ch on each link

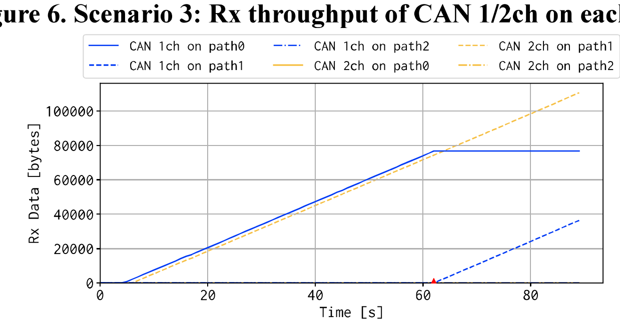

Figure 7. Scenario 3:Rx data volume of CAN 1/2ch on each link

Figure 6 shows the received throughput of CAN data on each link. Figure 7 shows the accumulated number of bytes received on each link for CAN 1/2ch. In this experiment, we limit the communication volume of CAN 1ch at path0 to 100 KB. CAN 1ch switches from path0 to path1 at the 62s in Figure 6, and similarly, Figure 7 shows that the received data volume of CAN 1ch increases only at path1 after the 62s and not at path0; CAN 2ch upload is always performed over path1 during this experimental period.

Based on these results, our method can adequately perform the upper data limit-based link selection. On the other hand, link switching is performed at less than 80KB in Figure 7, which is different from the 100KB limit. The difference is because the upper data limit is evaluated against the entire UDP payload length, while the data volume per flow shown in the figure is based on the MUP payload length excluding the MUP header length (16 bytes). The CAN data used in this experiment is about 80 bytes per packet, and about 20 percent of the communication volume, such as the MUP header, is measured as overhead.

Accurate data volume measurement requires collaboration with CHF in the IRIGATE 5GC, overhead measurement in N3IWF, and collaboration with MNOs. The CHF measures the amount of data through UPF but may not consider the overhead of the IPSec header, keep-alive communication, and fragmentation associated with tunnel control between N3IWUE and N3IWF. Accurate measurement requires instrumentation at N3IWF and collaboration with MNOs/MVNOs, the latter of which can be effectively achieved by acquiring data volume via an API of the Network Exposure Function (NEF).

6. Conclusion

This study focuses on using multiple communication links in a connected car. We propose a link selection method that enables appropriate cost distribution for communication link cost-bearers and application beneficiaries in the IRIGATE system. We introduced Link Selector to adapt to the further expanding use-case of connected services where various users rely on various communication links. Experiments have shown that the Link Selector is capable of static and dynamic link selection for each communication flow of an application.

In the future, the diverse needs for IoV will emerge. The IoV operator must promote utilizing multiple communication links and build a system that can provide high-capacity and high-quality communications as a foundation for upcoming services while ensuring that each beneficiary bears their costs fairly. Furthermore, collaboration between IoV operators and telecommunications operators is necessary to respond to this need more widely and improve communication control's accuracy and sophistication. The development of the proposed method will enable the provision of advanced connected services in connected cars and IoV and contribute to the further development of the mobility society.

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