A cost-effective SCTP extension for hybrid vehicular networks

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Abstract: Connected vehicles are promoted with the use of different communication technologies for diverse applications and services. There is an ongoing debate in the research and industry communities whether short range communications based on IEEE 802.11p or cellular based on 3GPP LTE should be used for vehicular communications. We propose a mechanism to utilise both short range and cellular communications simultaneously in a cost efficient way while providing the required quality of service to the users. A host connected to multiple networks is referred to as a multi-homed node and SCTP (Stream Control Transmission Protocol) is an IETF standard which supports multi-homing. We propose an extension to SCTP that takes into account not only path quality but also the cost of using each network. It is shown that the combination of QoS and cost information increases economic benefits for provider and end-users, while providing increased packet throughput.

Keywords: SCTP, cost efficiency, hybrid network architecture, heterogeneous vehicular networks, LTE, DSRC

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1 Introduction

Recent advancements in communication technologies have imparted vehicles with rudimentary intelligence that can be used for regular traffic update, energy efficient driving thus helping in reducing the workload on the driver. Even though off-board information through communication channels has been sparingly used so far, vehicular networks have the potential to be the pivotal technologies for the development of the next generation intelligent vehicles^[1]. DSRC (Dedicated Short Range Communication) and cellular (LTE) access technologies are predominantly used for V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) communications. In general, safety related applications have low latency requirements,

high priority and their range is small (neighboring vehicles or Roadside Units)^[2]. DSRC is proposed as the main technology that can support these applications. On the other hand, comfort and infotainment applications require longer range, higher data rates and have may higher tolerance on latency. Such applications can be served also by cellular or other wide area access technologies and include:

- Media download/stream from remote server, e.g. video download, web-radio.
- Internet/Cloud connectivity, e.g. personal data synchronization.
- VoIP services for vehicles.
- Co-operative local services, e.g. local electronic commerce, vehicle relation management.
- Internet-of-Things services, e.g. eco-driving as-

Figure 1 Reference hybrid network architecture in a vehicular scenario

sistance, remote-diagnosis

Therefore, HNA (Hybrid Network Architectures) will be required to ensure efficient data dissemination in typical vehicular environments as shown in Fig. 1. This has also been pointed out of the review of Heterogeneous Vehicular Networking in Ref. [3], where cellular communications are promoted for V2I and DSRC for V2V collaborative communications. In such environments, a node equipped with multiple network devices and connected to multiple networks is referred to as multi-homed. SCTP^[4] is an IETF standard, which supports multi-homing. However, original SCTP multi-homing functionality is only used when the primary interface becomes unavailable. In addition, the usage of cellular networks comes with a hefty price compared to nearly free usage of DSRC, which has to be taken into consideration when using the service.

To this end, in this paper we present a new cost effective technique for utilization of network resources in a loosely coupled HNA, where each node is simultaneously connected to (at-least) two networks (e.g. DSRC, LTE). The proposed mechanism considers both the QoS (Quality of Service) requirements of the application, as well as the potential cost of using individual networks. The overall objective is

to increase cost-efficiency of the network provider by controlling the off-loading ratio of individual traffic flows. Classical existing switching schemes focus on improving only the throughput with constraints on QoS without considering the cost of using each network or only looking at user perspective and overlooking the provider.

The remainder of this paper is structured as follows. Section 2 presents related works on SCTP and dynamic access network selection. The proposed cost-effective SCTP extension, including the cost model and path selection algorithm, is presented in section 3. Its performance is analysed in section 4 and section 5 concludes this paper.

2 Related works

SCTP is described in RFC 4960^[4]. The main purpose of SCTP is to enable use of an alternative network interface when the primary interface fails. Data chunks are transmitted over the primary network interface by default. However, retransmissions may be sent over the alternative interface(s). Once a path is selected, both data and ACK will be transmitted over that path. Kashiara et al.^[5] and Fracchia et al.^[6] extend the default SCTP multi-homing sup-

port, so that switching can be performed dynamically using decision criteria such as minimum RTT (Round Trip Time) and estimated available bandwidth. A QoS-driven extension of SCTP proposed by Cao et al.^[7] is used to improve the vertical handover mechanisms in heterogeneous networks by analysing the service stability and capacity of each path.

An extension of SCTP to utilize multiple interfaces simultaneously has been drafted by IETF, but has not been standardized yet^[8]. It specifies how multiple paths are simultaneously used, based on a Round Robin Scheduling, to benefit from all available network interfaces. The concept is dubbed as CMT (Concurrent Multipath Transfer) SCTP. Three modifications to standard SCTP are proposed to (i) split Fast Retransmissions, (ii) maintain separate congestion window for each path and (iii) delay acknowledgements also for out-of-sequence packets. CMT-SCTP has been extended in Refs. [9-11] so that scheduling can be performed more efficiently exploiting RTT, error rate and buffer size in the decision metric. The issue of buffer blocking in CMT-SCTP due to out-of-order deliveries, when the multiple paths have uneven bandwidth, is addressed in Ref. [12] with the introduction of virtual connections. These virtual connections are logical partitions of a physical network interface managed by a load-balancing algorithm it can preserve better performance than simple CMT-SCTP. The same problem is targeted in the DAPS (Delay-Aware Packet Scheduling)^[13] which considers delay diversity at the sender. This is extended by Chan et al. in Ref. [14] taking into account the variations in the delay and proposing a Jitter-aware packet scheduling scheme.

The work of Hou et al.^[15] proposes an integrated transport layer based on SCTP, called oSCTP, which offloads 3G traffic on Wi-Fi network to reduce cost. A utility and cost-based function is formulated to control the amount of load to put on 3G network to maximize user's benefit. The strategy assumes user utility function, $U(x)$, and network cost function, $C(x)$, are based on link throughput, x . User utilizes the maximum possible throughput on Wi-Fi at all points of time and when it is not sufficient, user

transmits on 3G only to fill in the slack, but no more. During each 1 s interval, packets are scheduled on the path with the smallest RTT that has congestion window open, utilizing both interfaces as in CMT-SCTP. However, the load balancing mechanism in this technique is quite primitive. Existing studies show that simple offloading to Wi-Fi is not optimum as cellular networks evolve and provide higher rates at cheaper prices. In addition, the utility and cost functions considered in this work are fixed for all data traffic. This does not allow for dynamic offloading according to the type of traffic and network dynamics. Further, the requirement of frequent (1 s) heartbeats in order to estimate available bandwidth and RTT make it unsuitable for dense vehicular networks due to the increased overhead incurred.

A technique for access network selection for terminals in multihoming scenario is proposed in Ref. [16]. The selection is based on an Application Policy implemented by a central controlling server. The Application Policy considers both user and provider preferences, e.g., UE (User Equipment) battery life, available CPU/Memory resources, status of different network interfaces, traffic status of different access networks, and SLAs (User Service Level Agreements). This technique builds on-top of media independent handover standard to dynamically switch access networks. However, it does not foresee frequent network switching or simultaneous use of multiple networks, which results in inefficient resource pooling.

3 Cost-effective SCTP

3.1 System model

This work aims to solve the problem of dynamically selecting available interfaces to cost-efficiently transmit packets in multi-homed vehicles utilizing a conceptual HNA (Hybrid Network Architecture) depicted in Fig. 2. This technique allows the network provider to influence the behaviour of the user, in terms of network selection, in order to balance between QoS for the user and the operation costs of the

network provider. User QoS is maintained by selecting the best path according to a QoS metric, e.g. minimum RTT or maximum available bandwidth, while the available paths for each user is restricted by the guidelines of the network operator. The system model assumes users with multiple network interfaces such as LTE, Wi-Fi, DSRC, and WiMAX, where at least one is a paid network. In this paper we only present a scenario where vehicles are equipped with LTE and Wi-Fi. A monitoring server, namely HTLS (Hybrid Transport Layer Server) in this technique, residing in provider core, computes and disseminates the network usage policies according to the cost model in section 3.2.

3.2 Cost model

There are lots of research works lately looking at mobile data offloading from an economic prospective rather than simply system's performance point of view. Paolini in Ref. [17] and Dhawan et al. in Ref. [18] approach the problem using CAPEX and OPEX¹⁾ analysis of different systems, i.e. macro-cells, femto-cells, Wi-Fi APs (Access Points) etc. These two works show how the total cost could be reduced by introducing more small cells and integrate Wi-Fi with cellular in order to offload the later. Both these two works assume a fixed proportion of mobile data to be offloaded, e.g. 60% as reported in Ref. [19], in their calculations for economic gains. On the other hand, Gao et al. in Ref. [20] and Lee et al. in Ref. [21] provide analytical models based on game theory in order to find the equilibrium of offloading or the economic benefits of offloading according to a certain pricing scheme.

We base our proposal on the findings of the work in Ref. [21], focusing on the offloading ratio in order to have economic benefit for both consumers and provider. According to that work, users are modelled with four attributes, (i) how much money they can pay (willingness to pay, γ), (ii) how many data they want to use (traffic demand, ϕ), (iii) how long

their data can tolerate (delay profile, α), and (iv) how they move (Wi-Fi contact probability, e). It assumes that the monopoly provider knows users' attributes and strategies a priori, i.e. the user profiles. For example, this information can be available to the cellular network provider through its UDR (User Data Repository), SPR (Subscriber Profile Repository) and HSS (Home Subscriber Server). The market can be modelled based on a two-stage sequential game (e.g. Stackelberg game). At the first stage, the provider decides on the pricing parameters (p) as a leader, and at the second stage, each user is a price-taker as a follower and chooses its LTE+Wi-Fi²⁾ traffic volume $\mathbf{x}$. The analysis results are carried out based on the equilibrium of this game assuming N total users and $\hat{N}$ users per cell. The user's net-utility is defined as $U(\mathbf{x})$ and the provider's revenue as $R(p)$.

$$U(\mathbf{x}) = \sum_{t \in T} \gamma(t) x^\theta(t) - m(p, \mathbf{y}(\mathbf{x})), \quad (1)$$

where $\theta \in (0, 1)$ is the price sensitivity, $m(p, \mathbf{y}(\mathbf{x}))$ is the daily payment charge for usage of LTE network, and

$$R(p) = \sum_{i \in N} m(p, \mathbf{y}_i(\mathbf{x}_i)) - \sum_{i \in N} c(\mathbf{y}_i(\mathbf{x}_i)), \quad (2)$$

where $c(\mathbf{y}) = \eta \sum_{t \in T} y_i(t)$ is the network cost to handle the LTE traffic with η the cost per unit of data^[22].

Off-loading indicator. The offloading indicator quantifies how much LTE data is offloaded, (i) aggregate LTE traffic ratio κ_{avg} , and (ii) peak LTE traffic ratio κ_{peak} .

$$\kappa_{\text{avg}} = \frac{\sum_{t \in T} Y(t)}{\sum_{t \in T} X(t)}, \quad (3)$$

$$\kappa_{\text{peak}} = \frac{\max_{t \in T} Y(t)}{\sum_{t \in T} X(t)}, \quad (4)$$

where the transmitted total traffic and LTE traffic over a cell at time t , $X(t)$, $Y(t)$ are

$$X(t) = \hat{N} \int_0^{\Phi_{\max}} x_\Phi(t) dF_\Phi, \quad (5)$$

¹⁾ CAPEX = capital expenditures, OPEX = operational expenditures.

²⁾ We use "LTE" to refer to a cellular network in general.

Figure 2 CE-SCTP reference system architecture

$$Y(t) = \hat{N} \int_0^{\Phi_{\max}} \sum_{d=0}^D b_{\Phi}^d(t-d) x_{\Phi}(t-d) dF_{\Phi}, \quad (6)$$

and $b_{\Phi}^d(t-d) = \alpha_{\Phi}^d(1 - e_{\Phi}^d(t))$ is the portion of the traffic generated at time t which is transmitted through LTE at time $t+d$. It is clear that as users delay more traffic, the aggregate LTE traffic ratio κ_{avg} provably decreases, since more traffic can be offloaded through Wi-Fi.

Opt-saturated and opt-unsaturated are two defined notions, which characterize the regimes under which how much traffic is imposed on the network for the equilibrium price. In general, as traffic demand gets higher compared to the LTE capacity, the network becomes opt-saturated, and vice versa. For a unique equilibrium price p^* , the network is said to be opt-saturated if the network is saturated at p^* , vice versa (Fig. 3).

Theorem 3.1 in Ref. [21] states that for flat pricing³⁾ if the cost of the unit volume of the LTE traffic $\eta < (\kappa_{\text{avg}} \Phi_{\max}^{1-\theta})^{-1}$ the net-utilities of all subscribers increase and the provider's revenue at equilibrium increases as (i) κ_{peak} decreases in the opt-saturated case, and (ii) as κ_{avg} decreases in the opt-unsaturated case.

Figure 3 Provider's revenue in flat pricing—opt-saturated and unsaturated regimes^[21]

3.3 Proposed cost-efficient scheduling scheme

The main idea of the proposed scheme derives from the theorem presented in section 3.2, where the economic benefits of both provider and users are increased as κ_{avg} decreases and $\eta < (\kappa_{\text{avg}} \Phi_{\max}^{1-\theta})^{-1}$. If the inequality does not hold, provider has losses, so for a given η , $\Phi_{\max}$ and θ , which can be seen as system parameters, there is a threshold on the offloading ratio, below which the provider is profitable and the end-user has economic benefits as well.

We assume that the price schemes available or those that will be available for vehicular customers, are in equilibrium. Therefore, the user of flat pricing

³⁾ The theorem is valid also for other pricing schemes.

should aim to have $\eta < (\kappa_{\text{avg}} \Phi_{\text{max}}^{1-\theta})^{-1}$ so the net-utilities will increase according to Theorem 3.1 in Ref. [21], knowing the regime we are. For a fixed η , θ and Φ_{max} we can only control the offloading ratio. For example as shown in Fig. 4 for a given $\eta = 0.1$ \$/MB, the maximum off-loading ratio for aggregate LTE traffic is 0.7 and 0.31 for a maximum daily demand of 200 MB and 1 GB assuming $\theta = 0.5$, while it lowered to 0.24 and 0.08 for $\theta = 0.3$, respectively. This shows the effect that both daily demand from the users and how much the users value that data have on the cost efficiency of mobile data offloading.

Figure 4 Off-loading ratio κ_{avg} for different traffic demands

In the light of these findings, we propose a cost-efficient transport protocol based on SCTP, named CE-SCTP, for hybrid vehicular networks. The architecture borrows concepts from 3GPP LIPA/SIPTO^[23], with the most important enhancement of the proposed architecture being the monitoring server, which provides the HTLS (Hybrid Transport Layer Support) function. It performs several functionalities in a RESTful manner, interacting with the underlying cellular and wireless networks, as well as external hosts, which include:

- Monitor data usage for both cellular and wireless networks. In order to calculate the offloading indicator, the mobile operator needs to keep track of all traffic in its network and offloaded traffic through the wireless network.
- Provide advice during a connection setup on

κ_{avg} . During a SCTP connection setup, the remote server will contact the monitoring server to get the most recent off-loading indicator for cost-efficient data transfers, based on the connection requirements and other SLAs (Service-Level Agreements).

- Provide interfaces to EPC (Evolved Packet Core). In order to be able to monitor traffic and provide the advice, the monitoring server should provide interfaces to the EPC. These include: (a) RESTful API interface to clients for requesting κ_{avg} threshold, (b) an interface to underlying networks for obtaining network traffic information, (c) HSS/SPR interface for subscriber-specific information that may influence policy decisions.

The overview of the CE-SCTP algorithm is presented in Fig. 5 and is divided into two parts, the user plane and the network provider plane. Initially, the user has to identify the available interfaces and based on a selection procedure mark one as primary. This will be used for the association establishment. After the association is established, all available interfaces can be used for data exchange, according to the path selection algorithm. On the network provider side, the HTLS server monitors the traffic and keeps track of cost-model parameters offline. During the association establishment, it evaluates the cost and advises the users with a particular network usage policy.

Figure 5 CE-SCTP overview algorithm

The association establishment procedure is depicted in Fig. 6, where the 4-way standard SCTP association establishment handshake is extended with the exchange of OTR (Offloading Threshold Re-

quest) and OTA (Offloading Threshold Acknowledge) control chunks. OTR and OTA chunks must be used to request and acknowledge the corresponding offloading ratio threshold for a particular association. The format to carry application characteristics should follow SCTP standard representation of optional/variable-length parameter (section 3.2.1 of RFC 4960^[4]).

Figure 6 CE-SCTP association establishment

After the association is established, the path selection procedure is performed as described with the flowchart in Fig. 7. Two QoS metrics are evaluated in our proposal; minimum RTT and maximum available bandwidth, however, this is not a limiting factor. These metrics are calculated from the received ACK packets. In addition, HEARBEAT packets are sent on all interfaces periodically (every 10 s) in order to check their availability and potentially update the QoS metric for a path that has not been selected during the previous time interval.

Figure 7 CE-SCTP path selection algorithm

Examples of data flow in both single-path and

CMT-enabled SCTP are presented below. HB (Heartbeat chunks) and HB-ACK (Acknowledgements) are sent periodically (10 s) on each interface to monitor status (interface availability and QoS metric). Data exchange starts on the primary interface (assume the LTE). Data and acknowledgements follow the same path. Meanwhile, user keeps track of data usage on each interface and upon receipt of a SACK, QoS metric on that path is updated. During path selection the “best” path is selected according to QoS metric. If the DSRC interface has better QoS, traffic is switched to that interface (Fig. 8(a)). When user’s ratio gets greater than the enforced network usage policy (e.g. ratio > 0.31), LTE interface cannot be selected, even though it has better QoS. Then, data is switched to the DSRC interface (Fig. 8(b)). After user’s ratio is below the enforced usage policy, data can be sent again over the LTE interface (as long as it still has better QoS). Finally, for CMT-enabled CE-SCTP (Fig. 8(c)), where both interfaces can be used simultaneously, when user’s ratio gets greater than the enforced network usage policy (e.g. ratio > 0.31), LTE interface cannot be selected. After user’s ratio lowers below the enforced usage policy, data can be sent again over the LTE interface.

4 Performance evaluation

In this section we present the performance evaluation of CE-SCTP in the reference highway scenario of 2 km depicted in Fig. 1 using Network Simulator 3 (version ns-3.23). We have varied both the number of nodes from 20 to 200 in the reference area, the number of connections from 5 V2V (Vehicle-to-Vehicle) connections to 50, and the data rates of those connections from 100 kbit/s to 200 kbit/s. We have assumed a homogeneous demand from users with $\Phi_{\text{MAX}} = 1$ GB and price sensitivity $\theta = 0.5$. The operator works with a cost per unit $\eta = 0.1$ \$/MB, which as reported in section 3.2 gives a maximum offloading ratio $\kappa_{\text{avg}} \approx 0.31$ in order to have profit. In this evaluation, every connection is the same; thus a maximum ratio of 0.31 is employed on each CE-SCTP transfer. We have evaluated three networking

Figure 8 Examples of path selection algorithm. (a) Single path CE-SCTP QoS trigger; (b) single path CE-SCTP cost trigger; (c) CMT-enabled CE-SCTP cost trigger

architectures: (a) pure Ad hoc wireless, (b) pure cellular and (c) hybrid with four different scheduling algorithms in V2V scenarios. The routing protocol that is utilized for the Ad hoc network is CLWPR (Cross-Layer Weighted Position-based Routing)^[24], which we have proposed as more efficient solution for vehicular communications. The random scheduler selects one of the available network interfaces randomly, while in RTT and BW (Bandwidth) schedulers the selection is performed based on minimum RTT or maximum available BW, respectively. Finally, cost scheduler implements a basic CE-SCTP concept, where the selection is based on maximum available BW or minimum RTT, keeping also the corresponding off-loading ratio below the threshold $\kappa_{\text{avg}} = 0.31$.

The most evident result from this evaluation is that multi-homed networks can provide higher throughput, which supports our proposal for hybrid network architecture (Figs. 9(a), 10(a), 11(a)). Using both network interfaces (LTE & Wi-Fi) concurrently, increases the throughput of a single network in all configurations as expected. It is worth noting that the resulting throughput from the aggregated networks does not equal with the sum of the throughput of the two single networks. This is due to the overhead of SCTP and the issues of buffer blocking as reported in the related work section. However, in low

traffic demand, Ad hoc wireless (Wi-Fi) can support the demand by itself and there is lower need to off-load (Fig. 9(b)). This is beneficial for both users and operators. However, as traffic demand increases, Ad hoc wireless network gets congested and schedulers using available bandwidth as indicator start shifting traffic towards the LTE network (Figs. 10(b), 11(b)). The random and RTT-based schedulers show better performance in terms of achievable throughput as the number of nodes/connections increases compared to available BW scheduler. However, they are both non-profitable for the cellular provider in every scenario, which makes them undesirable. The scheduler based only on available bandwidth shows better performance in low traffic demand and its off-loading ratio is well below the κ_{avg} threshold. However, when demand increases, the uncontrolled shift of traffic on the LTE network reduced the profit and in certain cases becomes unprofitable. The cost scheduler shows similar throughput results as the BW scheduler, but with the added benefit of larger profits for the operator. Further, the distribution of traffic between the two networks among individual users varies depending on the switching scheduler.

While Random scheduler keeps traffic disparity relatively low even for large number of users (Figs. 12(c) and 12(d)), RTT and BW schedulers can not control it due to the isolated observations

Figure 9 Scenario with data flow 100 kbit/s. (a) Throughput; (b) usage ratio

Figure 10 Scenario with data flow 150 kbit/s. (a) Throughput; (b) usage ratio

Figure 11 Scenario with data flow 200 kbit/s. (a) Throughput; (b) usage ratio

Figure 12 Traffic Distribution among users on the two networks. (a) 20 nodes@150kbit/s-Wi-Fi usage; (b) 20 nodes@150kbit/s-LTE usage; (c) 50 nodes@100kbit/s-Wi-Fi usage; (d) 50 nodes@100kbit/s-LTE usage

for RTT or estimated BW performed by individual users (Fig. 12). This is manifested by the large distribution in the box-plots of Fig. 12, which illustrates the distribution of bytes send from users over different network interfaces (Wi-Fi and LTE). This issue is important for individual user pricing as well as for the efficient provision of the radio resources. The system, from provider's point of view, might be cost-efficient in certain conditions, i.e. operate below κ_{avg} , but there are users who use their LTE quota more than others, resulting in uneven resource distribution.

With the introduction of Cost metric in the selection of the network interface, the distribution is reduced and is more predictable from the network operation point of view.

5 Conclusion

Multihoming is one approach to provide reliable vehicular communications. In this paper, we take up the challenges involved in supporting multihoming at transport layer. Using the theorems of economic

offloading introduced in Ref. [21], we propose a cost-effective SCTP extension. The characteristic of the cost model we employed, is that it considers both the network provider and the end-user perspective and aims to increase the economic benefits of both. The simulation-based analysis has validated the cost-effectiveness of the proposed protocol, while providing the best quality of service depending on the selected metric.

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