An Integrated Architecture for Multi-homed Vehicle-to-Infrastructure Communications

Hamada Alshaer
Etisalat BT Innovation Center (EBTIC)
Khalifa University, UAE.
Emails: {hamada.alshaer@kustar.ac.ae

Thierry Ernst and Arnaud de La Fortelle
Mines ParisTech
Ecole des Mines de Paris, France.
Emails: {Thierry.Ernst,Arnaud.de_La_Fortelle}@inria.fr

***Abstract*—We develop an intelligent distributed quality-of-service (QoS) control scheme which inter-operates between mobile routers, managing vehicular networks mobility, and road communication gateways (RCGs). This scheme manages vehicle-to-infrastructure (V2I) communications by enabling multi-homed vehicular networks to evenly distribute traffic among egress links of their mobile routers based on vehicular communication policies, available bandwidth and performance metrics of selected routing paths with correspondent nodes (CNs). In this scheme, the data control plane is considered as a collaborative entity and specifies detailed operations to be performed in the mobile routers and RCGs. Simulation experiments show that our proposed scheme can improve the congestion window (CWND) of TCP and the e2e packet loss of video traffic, despite network mobility. It also guarantees the service parameter settings of each uplink and downlink connection, while achieving reasonable utilization efficiency of network resources.**

I. Introduction

Highway communication systems gain momentum efforts to set up a transport communication network which can enable vehicles to communicate with each other and with roadside communication stations. Some highway tests have already been completed for the vehicle infrastructure integration (VII) systems [1], which aim to reduce accidents and congestion. Because of wireless channel fading and network mobility, QoS provisioning in wireless and mobile networks is more challenging than in fixed networks [2], [3]. Multi-homing in Intelligent Transportation Systems (ITSs) often refers to the connection of vehicular mobile networks (NEMOs) to multiple Internet service providers (ISPs) through different wireless and radio communication technologies. Multi-homing enables vehicular NEMOs to be reached anywhere anytime under varying network topologies and communication circumstances [4].

Fig. 1 shows our architectural overview of typical intelligent transportation services oriented in multi-homed vehicular networks proposed for reliable vehicle-to-infrastructure (V2I) communications. Mobile routers, road communication gateways (RCGs), home agents and application servers inter-operate within this architecture to guarantee high quality in provisioned services and applications for mobile networks and users on-board vehicular networks. The functionality of entities in this architecture is described in what follows.

- **Road communication gateway (RCG)**: A RCG is managed by a network service provider (NSP). The RCG selects a downlink wireless, radio or satellite channel and allocates bandwidth for downstream traffic destined to vehicular networks. It offers both reservation-based and on-demand Internet access services. The RCG also computes and allocates routing paths with HAs.

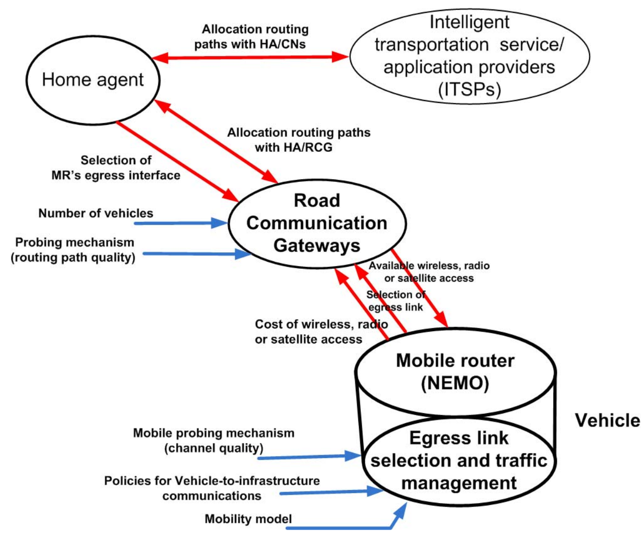

Fig. 1. Architecture for vehicle-to-infrastructure communications.

- **Network service provider (NSP)**: The NSP owning the RCGs sets optimally the price of bandwidth for Internet access to maximize network revenue. The price of bandwidth for reservation-based Internet access is set by the NSP on a longer time scale and is assumed to be fixed here.
- **Mobile router (MR)**: The MR performs wireless, radio or/and satellite access as well as routing path selection through the RCG in a service area using either reservation or on-demand mode. The decision on selected routing path and wireless, radio or satellite access is made in the MR to support QoS-sensitive applications while minimizing the cost of wireless, radio or satellite access.
- **Intelligent transportation service provider (ITSP)**: The ITSP owning the MRs decides to buy bandwidth from the NSP for reservation-based wireless, radio or satellite access in different service areas so that the long-term cost of Internet access is minimized. ITSPs are

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also registered with a **HA** to reach vehicular networks anywhere anytime. Recall that the HA through NEtwork MObility Basic Support Protocol (NEMO-BSP) [5] can trace and localize vehicular mobile networks by binding their Home-of-Address (HoS) with Care-of-Address (CoS) [5].

This paper introduces a distributed QoS control scheme which inter-operates between mobile routers configured on vehicular mobile networks and road communication gateways to: (i) establish reliable connections based on defined vehicular communication policies, users' preferences, ITSP service level agreements (SLAs) with on-board users, (ii) select and switch autonomously to the best available routing path with CNs, (iii) manage the mobility of vehicular networks and (iv) optimally distribute traffic among the wireless and wired segments of selected routing paths with HAs and CNs.

The rest of this paper is structured as follows. In Section II we describe our proposed scheme for V2I communications and explain the operation of the entities integrated in this scheme. Section III along with Section IV describe the mechanisms used for computing, selecting and allocating routing paths with HAs and CNs. In Section V we evaluate our proposed e2e QoS scheme and report its performance. Finally, Section VI draws a conclusion to this paper.

II. Proposed e2e QoS scheme

Fig. 1 shows that NEMO, via (MR), can reach Internet through multiple operators by using different communication networks. The operation of medium access control (MAC) services supported through these communication technologies is connection-oriented. A connection is defined as a unidirectional mapping between MR and road communication gateways MAC peers for the purpose of transporting a service flow's traffic. A service is a unidirectional flow of MAC service data units with predefined QoS parameters. A connection is defined by its unique connection identifier (CID) based on which it is implicitly provided. To accommodate upper layer applications with different service requirements, our proposed scheme defines two types of MAC scheduling service: non-elastic and elastic services. Each connection is categorized into one of these two service categories according to the property application carried by this connection.

A road communication gateway can request bandwidth for each downstream connection by sending a stand-alone MAC header. Although the bandwidth is requested for a connection, the grant is issued to a corresponding road communication gateway which decides about the allocation of granted bandwidth. Thus, the RCG can perform some connection level functionalities performed by the base stations (BSs), which limit the signaling overhead while guaranteeing the QoS required for traffic connections. In what follows we introduce the first entity in our proposed e2e QoS scheme architecture, which is responsible for selecting egress links of MRs with road communication gateways.

A. Available bandwidth measurement unit

This unit is integrated in our proposed scheme to measure the available bandwidth on egress links. It obtains the instant bandwidth request of each connection according to its buffer length and MAC headers required to transmit backlogged traffic. This bandwidth request is upper-bounded by the eligible bandwidth request of connection, which is calculated as:

$$r_i^e = max\{\frac{R_i^{max}}{8} \times [t - S_i(t)], 0\} \tag{1}$$

where r_i^e is the eligible bandwidth request of connection i, R_i^{max} is the maximum sustained traffic rate in (bits/second) of this connection and t is the system (i.e, MR or RCG in upstream or downstream connections, respectively) time. $S_i(t)$ represents the service timer value of connection i at time t. The MR allocates traffic connections whatever available bandwidth on the selected routing paths to guarantee their QoS requirements.

B. QoS enforcement unit

This unit maintains a QoS timer (priority value) for each non-elastic upstream and downstream connection running in the MR and road communication gateway, respectively. The QoS timer enforces the service rate of connection to meet a guaranteed value. The QoS timer is synchronized with the system clock and ticks with the following value upon the service of each packet in the corresponding connection:

$$A_i = \frac{8 \times B_i}{\rho_i} \tag{2}$$

where A_i is the increment of connection $i's$ service timer, upon the service of a packet of size B_i bytes. ρ_i is the service timer value which should be R_i^{max}. However, for the QoS timer, the value of ρ_i should be R_i^{min}, i.e., the minimum reserved traffic rate (in bps) of connection i. The reason behind designing two virtual times for a connection requiring minimum service rate is to have the received service rate guaranteed but not limited at its minimum reserved traffic rate. The operations performed by the QoS enforcement module include two steps: (i) For each non-elastic (bandwidth guaranteed) or elastic (non-bandwidth guaranteed) connection i, divide its bandwidth request r_i into bandwidth guaranteed (BG) part and non-bandwidth guaranteed (NBG) part, i.e., r_i^{BG} and r_i^{NBG}, according to the corresponding value of QoS timer, denoted as $Q_i(t)$, i.e:

$$\begin{aligned} r_i^{BG} = min\{r_i, \frac{R_i^{min}}{8} \times [t - Q_i(t)]\}, \ Q_i < t \\ r_i^{BG} = 0, \ Q_i(t) \geq t \end{aligned} \tag{3}$$

where $r_i^{NBG} = r_i - r_i^{BG}$, which can be offered to BE connections.

The arrived packets or flows are scheduled onto an ingress link of MR if there is enough bandwidth to accommodate them such that their QoS requirements are guaranteed [6]. The connection admission and resource allocation functions are proactive which can be based on anticipatory utilization on egress links. However, the selection process of an egress link is based on specific policies integrated into MR for V2I communications or services provisioned through communication operators. For example, an egress link is selected because it offers the required service with reasonable cost; or it has enough bandwidth and guarantees high quality of traffic transmission.

C. Mobile Weighted Round Robin SSD

A mobile weighted fair queuing (MWFQ) scheduling service discipline (SSD) has been integrated into our scheme to serve traffic connections based on their class and capacity sharing of egress links. It allocates available bandwidth to traffic connections based on their priority class, but does not adapt incoming traffic data rate to the available bandwidth on egress links of MR. Fig. 2 depicts the flowchart of our proposed mobile weighted round robin (MWRR) SSD. The MR maintains a number of tables to manage traffic on egress links: Capacity of egress links table, $C[i][0]$, available bandwidth table, $BW[i][0]$, flow table, $FT[i][0]$, link table, $LT[i][0]$, weight table, $WT[i][0]$, number of flows table, $NFT[i][0]$, packet table, $PT[i][0]$, number of packets table, $NPT[i][0]$, $\forall i \in \{WLAN, satellite, GPRS, UMTS\}$. $C[i][0]$ records the capacity of egress links. $BW[i][0]$ records the available bandwidth on egress links. $FT[i][0]$ records the flows assigned to egress links. $PT[i][0]$ records the packets assigned to egress links. $LT[i][0]$ records the utilized bandwidth on egress links after admitting packets/flows. $WT[i]$ records the weights assigned to egress links based on the available bandwidth. $NFT[i][0]$ records the number of flows assigned to egress links. $NPT[i][0]$ records the number of packets assigned to egress links.

The MR uses probing to measure the available bandwidth on egress links. Each interface $''i''$ is assigned a weight,ω_i, based on the available bandwidth measured on this interface,γ_i ,as follows:

$$\omega_i = \frac{\gamma_i}{C_i}. \tag{4}$$

Equ.(1) calculates the bandwidth required for a traffic connection. The number of flows (NF) scheduled onto an egress link $''i''$ can be calculated as follows:

$$NF_i = \frac{\gamma_i}{r^e} \tag{5}$$

$$NFT[i][0] = NFT[i][0] + \lceil \omega_i * NF_i \rceil * r^e. \tag{6}$$

The number of packets (NP) scheduled onto egress links can be calculated as follows:

$$NP_i = \frac{\gamma_i}{L_p} \tag{7}$$

$$NPT[i][0] = NPT[i][0] + \lceil \omega_i * NP_i \rceil * L_p \tag{8}$$

where L_p represents the size of each packet scheduled onto the egress link $''i''$. The capacity of egress links in $NFT[i][0]$ and $NPT[i][0]$ is incremented by the bandwidth allocated for admitted flows or packets based on the flow or packet dispatching scheme, respectively. By calculating the number of flows or packets which can be dispatched onto egress links, traffic can be better balanced among egress links. This increases the utilization of egress links, while controlling the resource allocated for traffic connections with different QoS requirements. In what follows, we introduce the second entity in our proposed e2e QoS scheme architecture, which is responsible for computing and selecting routing paths with HAs and CNs. This entity consists of local and global traffic load balancing.

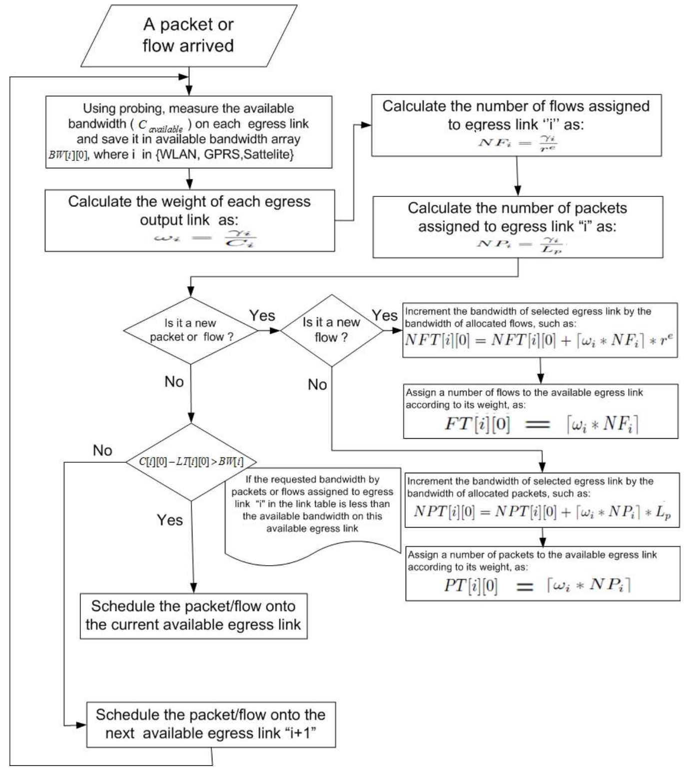

Fig. 2. Mobile weighted round robin SSD.

III. Local Traffic Load Balancing

The MR as well as other network nodes should ensure optimal or even distribution of traffic among output links so that traffic can be evenly distributed across the network [7], [8]. MNNs generate traffic connections at different data rates, where egress interfaces (output links) of MR as well as other network nodes serve traffic at different service rates. Based on the traffic arrival rates at each of the input links and service rates at the output links of any network node, optimal weights can be dynamically calculated for each output (outbound) link to upper bound the amount of transmitted traffic.

Usually, ISPs can only provide static routing for router access to better manage and control traffic in their network domains. To avoid managing BGP routing table, many networking systems perform link sharing based on the NAT mechanism or stripping traffic connections, packet or users into the different output links [8], [9]. This would increase the multiplexing gain by enabling traffic connections to efficiently use the capacity of output links. Note that the weights of outbound links should not be simply set proportional to their link rate or the number of next hops [10], instead it is better to be calculated based on the input traffic rate and available capacity measured or estimated at the output links.

When the weights are calculated at each output link of any network node between NEMO and correspondent nodes, then, traffic load balancing can be achieved by using a simple Class-Based Queuing (CBQ) or Weighted Round Robin (WRR) service scheduling discipline. In NEMOs, the service rates of output links change in function of time and geographical positions of NEMOs; therefore, our proposed mobile WRR SSD adjusts dynamically the weights based on the available bandwidth measured at the output links and network status. However, since routing protocols do not have self-knowledge of current traffic load of each link, they cannot achieve real traffic load balancing through the multiple links to the Internet for the inbound/outbound traffic. Thus, local traffic load balancing should be augmented with global traffic load balancing to avoid any eventual congestion and guarantee traffic load balancing across network.

IV. Global Traffic Load Balancing

Traffic connections contend to the available resources on the different routing paths which connect NEMOs through its MR and RCGs with home agents and correspondent nodes. Most routing-based techniques involve two stages: routing path calculation and selection. The process of routing path calculation can be either static or dynamic. Static route calculation techniques work effectively when traffic is fairly steady. In NEMOs, however, traffic over routing paths fluctuates over short time scale, particularly on route segments connecting NEMO with RCGs. Therefore, dynamic routing techniques should be used to dynamically calculate routes based on certain transient dynamic traffic information, such as: link congestion, number of contending connections, signal-to-noise ratio (SNR) and bandwidth availability. This information can be obtained by using either probe-based or broadcast approaches. In this paper, we employ a probe-based approach and an optimal broadcast approach to collect information regarding the status of the different routing paths connecting NEMO with CNs.

In the probe-based approach, before the MR routes traffic connections generated by MNNs, a RCG sends a probe packet to the HA serving NEMO. The probe packet collects the necessary information from the links and network nodes along the routes connecting NEMO and RCG with HA and returns to the RCG with the necessary information to select a routing path. In the broadcast approach, network nodes and RCGs transmit relevant congestion information periodically to all edge nodes including RCGs and NEMOs (MRs), respectively. RCG can send the probe packet either once for every handover performed by the NEMOs (MRs) or periodically after an interval τ [11].

The RCG sends traffic data using burst mode. Data is buffered and then sent on a routing path calculated and allocated for traffic connections. Since the duration of the transmitted data is short, the probe can be sent periodically after the interval τ. To reduce the control packet traffic (overhead) in the broadcast approach, the feedback information about a link can be sent to all edge nodes if the traffic load on the link exceeds a maximum congestion load threshold, ρ^{max}. Note that NEMOs through probing will be notified if there is a change on the congestion status from the previous value of the links connecting them with RCGs. By doing so, the core nodes and RCGs can eliminate sending status packets in certain intervals altogether, thereby ensuring that there is minimal feedback to all the edge nodes (RCGs) and NEMOs, respectively. It is noteworthy that additional memory overhead is needed at the core nodes to maintain the load status of their output links.

When the routing paths are selected statically or dynamically, one of these paths is selected for transmitting traffic. If the calculation technique for routing paths computes only a single path, the selection process of routing path is omitted; thus, the selection of routing path primarily applies to static routing path computation techniques that calculate multiple routes. In static routing path selection techniques, a fixed fraction of traffic is sent on each of the alternate routes. The amount of traffic sent on each alternate path is decided based on feedback information. Dynamic route-selection policies are based on feedback information, which operate as the dynamic route-calculation techniques. Using the information and the dynamic route selection policy, the data is transmitted on the selected route. Stabilization is a significant point in dynamic routing path calculation and selection techniques. It is possible that different NEMOs react to congestion simultaneously, which will result in oscillation between congested and uncongested states. Hence, additional constraints have to be incorporated to ensure that the MR does not keep switching all the traffic from one path to another every time the MR or the RCG receives update regarding congestion status of network links.

A. least-congested dynamic route calculation technique

Network core nodes measure traffic load, $\rho_{(i,j)}$, on each of its output link (i, j). Traffic load is expressed as the duration of all arriving bursts over the interval, τ, that is $\rho_{(i,j)} = \frac{\tau_s + \tau_d}{\tau}$, where τ_s and τ_d denote the duration of the bursts successfully transmitted and dropped during the interval τ, respectively. The traffic load of each link is calculated every τ units of time, where the routes are computed again. Let the weight, $W_{i,j}$, is based on a single or combination of metrics. One option is to set the weight function equal to the congestion metric, resulting in the least congested path. This metric may lead to long routes with a high number of hops. Therefore, while sending the burst on the least congested routing paths results in low packet loss probability at lower loads, under higher loads, longer routing paths will result in higher overall network traffic loads, thereby increasing the probability of contention. To avoid such a situation, we consider a weighted function based on congestion and hop distance:

$$W_{(i,j)} = \rho_{(i,j)} + 1 \qquad (9)$$

where $\rho_{(i,j)}$ is the offered traffic load on the link (i,j). This weighted function results in better performance in term of loss, since the minimal number of nodes are selected in a routing path, thereby reducing the probability of contention.

Another option is to define the weighted function based on congestion and propagation delay.

$$W_{(i,j)} = \rho_{(i,j)} + \frac{d_{(i,j)}}{d^{max}} \tag{10}$$

where $d_{(i,j)}$ is the delay propagation of the link (i,j) and d^{max} is the maximum delay propagation of any link in the network. This weighted function may result in better performance in terms of propagation delay and congestion, since minimum congestion and propagation delay on links are selected on a routing path, thereby reducing the congestion and e2e delay.

B. parameter selection

The duration after which the offered traffic load on a link is computed, τ, significantly affects the performance of the traffic load balancing algorithm. There are three factors which should be considered in selecting the value of τ: the amount of control overhead, the accuracy of algorithm and the effect of outdated information. The average traffic load obtained in larger value of τ is more accurate. A short value of τ will increase the control overhead in the network and load status computed during this interval may be not accurate. The selection of ρ^{max} is also critical, since the value determines whether the link is congested or not. Hence, the value of ρ^{max} should be chosen based on the desired operating load range of the network. Setting a low value to ρ^{max} will lead to better route selection decisions when the traffic load is low. However, when the operating loads are much higher, ρ^{max} will be ineffective, since ρ^{max} will signal congestion on all the alternate paths, thereby not providing any useful information for the edge node. On the other hand, setting a high value of ρ^{max} will result in good decisions at high loads. However, at lower load all the paths will not be congested between a source and destination. Hence, all the traffic will be sent on the primary path, resulting in congestion on this path.

V. Simulation and Results

To evaluate the performance of our proposed e2e QoS control scheme, we have integrated it, under OMNeT++, with NEMO-BSP [5] in the network topology shown in Fig. 3. In this, a multi-homed vehicular NEMO is connected to Internet through WLAN, UMTS and GPRS communication technologies. A single HA serves NEMO and enables MNNs and CNs to communicate based on NEMO-BSP. Along the simulation time, 3MB to 6MB files were constantly transferred from MNNs (host0, host1 and host2) to CNs. NEMO was moving at a random speed (10 m/s, 20 m/s, 30 m/s) to measure the effect of network mobility on the communication performance metrics. Most of the Internet applications use TCP/IP as an underlying transport protocol; therefore, we have conducted simulation experiments with the aims to: (i) analyze the TCP congestion window (CWND) size while the CBQ SSD is functioning in the MR, (ii) evaluate the performance of traffic splitting schemes, namely packet traffic and flow traffic splitting schemes(PTSS and FTSS) and (iii) evaluate the performance of the least congestion and minimum hop-based dynamic route calculation technique in reducing the impact of network mobility on video traffic. The TCP CWND bounds the amount of data which can be sent per round-trip time (RRT) of any connection. The slow start threshold (ssthresh) sets the value of the TCP CWND, which corresponds to the estimated available bandwidth along the selected routing path and accordingly regulates the transmission rate based on:

$$Bandwidth = \frac{1.22 * MTU}{RTT * \sqrt{L}} \tag{11}$$

$$ssthresh = bandwidth * RTT_{min} \tag{12}$$

where MTU denotes the maximum transmission unit, L denotes the loss probability along the routing path and $RTTmin$ denotes the minimum propagation RTT between MNN and its CN.

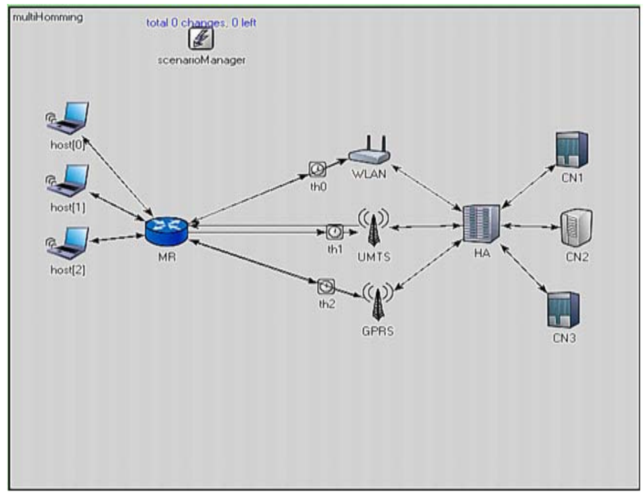

Fig. 3. Multi-homed NEMO simulation environment in OMNeT++.

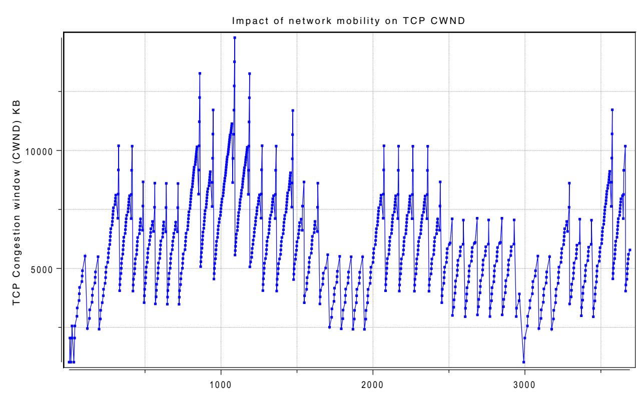

Fig. 4. The impact of network mobility on TCP congestion window.

As a result, Fig. 4 shows that the TCP CWND varies according to network mobility and selected routing path, where

MNNs could send at higher data rate when the MR selected the WLAN egress interface or NEMO was moving at low speed such as 10 m/s. Thus, NEMO should carefully select the egress interface according to network mobility and NEMO speed. Fig. 5 shows a result where NEMO speed was set to 30 m/s. It demonstrates that the FTSS performs better than the PTSS in term of TCP CWND, enabling MNNs to send at higher data rate. Furthermore, the TCP CWND appears to be more stable in case of FTTS than that resulting from the PTSS. This can be attributed to the fact that traffic packets which are forwarded to different egress interfaces in case of PTSS, their TCP connections converged to different ssthresh values based on Eqns.(11 and 12), and therefore the CWND size varies on short time scale, decreasing the e2e throughput. This explains the problem of the TCP CWND size, where competing connections might not be allocated equal network resources, because the TCP CWND size might converge to different CWND values.

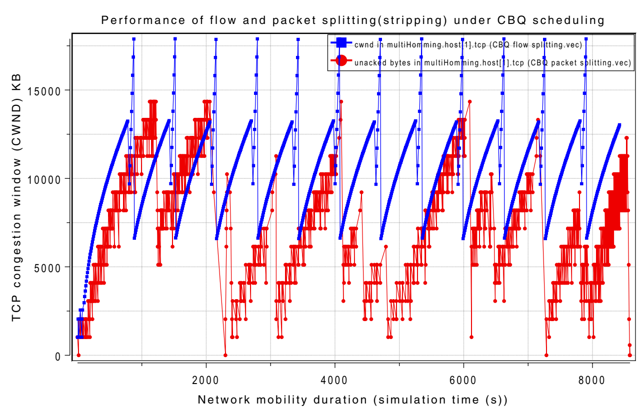

Fig. 5. Performance of TCP packet and flow splitting schemes under CBQ scheduling.

Fig. 6 shows that the proposed distributed e2e QoS control scheme performs better when the routes selection is based on the weighted function described in Eqn(9). This is represented by the low video traffic loss during network mobility ($0-3000$ s) where the probing duration was long and routing paths were selected based on the congestion and hop distance. Thereafter, however, the proposed scheme selects routing paths based only on congestion, where longer routes were selected for video traffic and hence a spike appeared, representing the increase in video traffic loss.

VI. Conclusion

Network mobility can significantly reduce the throughput of MNNs due to the variations of the TCP CWND on short time scale. This can be improved by enabling NEMOs to dynamically select routes based on the measured (probed) available bandwidth along the different routes connecting it with CNs. This paper has introduced an e2e QoS control scheme which integrates three main entities: Scheduling service discipline, traffic splitting, dynamic routing path computation, which ensure optimal multi-homing configuration for vehicular NEMOs

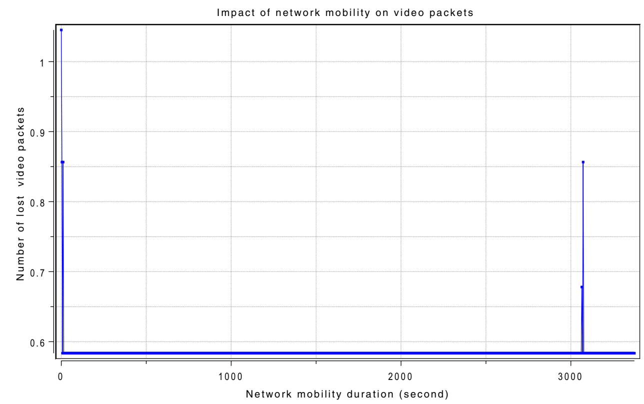

Fig. 6. The impact of network mobility and route selection on video packets.

by enabling MR and RCGs to optimally distribute traffic among egress interfaces with RCGs and routing paths with HAs and CNs, respectively. By integrating local and global traffic load balancing, each network node can contribute in optimally distributing traffic load across the whole network. Simulation results have shown promising performance of our proposed distributed e2e QoS control scheme which will be further developed to integrate other network entities that can ensure optimal multi-homing configuration for vehicular NEMOs.

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