Analytical model of RTT-aware SCTP

Konstantinos Katsaros, Mehrdad Dianati, Rahim Tafazolli
Institute for Communication Systems (ICS)
University of Surrey, UK
Email: {k.katsaros, m.dianati, r.tafazolli @ surrey.ac.uk}

***Abstract*—Connected vehicles are promoted with the use of different communication technologies for diverse applications. A host with multiple network devices is referred to as a multi-homed node. Stream Control Transmission Protocol (SCTP) is an IETF standard which supports multi-homing. However, original SCTP multi-homing functionality is only used when the primary address becomes unavailable. This paper presents an analytical model for a modified SCTP with multi-homed hosts, which selects the primary network address using a utility function based on minimum round trip time.**

***Index Terms*—stream control transmission protocol, round trip time, analytical model**

I. Introduction

Governmental bodies in the U.S. (National Highway Traffic Safety Administration), Europe (European Commission) and Asia are in the phase of standardisation and regulation of the different technologies that will facilitate connected vehicles. In addition, several projects are conducting research with field operation tests in order to assess the impacts of Intelligent Transportation Systems (ITS) applications with respect to safety, traffic efficiency and environmental impacts, e.g. DRIVE-C2X[1]. Most of the safety-related ITS applications rely on broadcast vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications. Such applications are best served by dedicated short range communication (DSRC) systems [1]. However, there is a number of applications, mainly for traffic management and infotainment, which require unicast data dissemination. For example, applications presented in ETSI specifications [2] requiring unicast communications include Traffic Information Recommended Itinerary (TIRI), Fleet Management, Media Downloading, and general internet access. These applications can also be served by cellular networks.

Connected vehicles are equipped with more than one network devices, specifically DSRC and cellular, in order to connect with other vehicles or the infrastructure. A vehicle with multiple network interfaces and individual IP address assigned per interface, from different network providers, is referred as multi-homed. Typically, vehicles use only one network interface depending on the type of application. However, the proliferation of multiple network interfaces has promoted the development of multi-homing and multi-path technologies in vehicular communications. Such systems are an interesting research field, aiming to bridge the gap between intermittent, low capacity and low latency DSRC systems, and ubiquitous coverage, high capacity and high latency cellular systems.

[1]Available from http://www.drive-c2x.eu/project

Stream Control Transmission Protocol (SCTP) [3] is one Internet Engineering Task Force (IETF) proposed standard that supports multi-homing, by default as backup when primary IP becomes unreachable. It provides a message oriented data delivery, full duplex, congestion control, with reliable and partial reliable data transfer; characteristics wanted in a communication system for connected vehicles. There are several extensions to this protocol that exploit multiple network interfaces and paths available to increase throughput and reduce latency, which we review in section II. However, their results are based on simulation evaluation, without providing a robust analytical model. In this paper, an analytical model for a modified SCTP model is presented, which selects the primary network interface based minimum round trip time (RTT) such as the proposals in [4], [5]. The proposed work analyses SCTP throughput using a discrete Markov chain to describe congestion window evolution and queueing theory to estimate path's round trip time.

The remainder of the paper is organised as follows. Section II reviews related work on SCTP multihoming schedulers and the different utility functions employed to select the primary interface. In section III, the analytical model of basic SCTP and the modifications to account for the utility function are presented. The original and modified models are evaluated in section IV. Finally, section V concludes the paper.

II. SCTP Schedulers State-of-the-art

There are two approaches for scheduling in a multi-homed architecture. The first, is to select the primary path, where all packets are transmitted, according to a utility function. The second, is to utilise the Concurrent Multi-path Transfer (CMT) [6], where packets can be sent over multiple paths simultaneously, and the utility function is employed to calculate the utilization ratio among the paths. Examples of these two approaches are reviewed in the following subsections.

A. Single Best Path Selection

In SCTP with multi-homing support, only the primary interface is used. Alternate interfaces are considered secondary and used only to provide fault tolerance; i.e. retransmit lost packets to increase probability of successful reception and transmission of new packets when primary is declared inactive, in which case the secondary is turned primary. In [4], the selection of primary interface is based on two factors; round trip time (RTT) and estimated bottleneck bandwidth. RTT reflects the degree of congestion and the packet loss rate on a path. On the other hand, estimation of bottleneck bandwidth provides information on which path can provide enough BW for real-time communication. Similarly, Fracchia et al. [7] base their selection of the best path on the estimated bandwidth after a retransmission timeout occurrence. If a secondary path provides larger bandwidth than the current, the paths are swapped. This procedure is performed with a time hysteresis to avoid frequent path switches.

B. CMT Best Path Selection

In CMT-SCTP [6], packets arriving from the upper layer are scheduled simultaneously on the available paths in Round-Robin fashion. As reported in [5], this is not efficient because the throughput tends to get bounded by two times the throughput of the path with smaller bandwidth. This is due to the operation of SCTP, which schedules packets on a path as long as the congestion window on the path is open. In addition, missing sequence numbers in the receive window should be avoided. Since the receiver relays packets to the upper layer in sequence, existence of gaps prevents the receive buffer from flushing. To overcome the issues of Round-Robin scheduler, the authors in [5] propose two strategies: (a) *Lazy* schedules packets on the current path until the congestion window exhausts and then switch to the other, and (b) *Smallest RTT* always schedules packets on the path with the smallest RTT that has congestion window open. The *Lazy* scheduler tends to outperform the Round-Robin scheduler only when the disparity in the bandwidths of the two paths or the delays of the two paths is large. The *Smallest RTT* scheduler's throughput is almost equal (closer than 90%) to the Ideal[2] as it addresses the above two issues.

On the other hand, the authors in [8] use a cross-layer QoS metric to select the path to send. This metric combines the RTT of a path, as a macroscopic path quality indicator, and Frame Error Rate (FER) of the network device, as a microscopic wireless link quality indicator. This metric is calculated as follows:

$$CM = \frac{1}{RTT \times \sqrt{FER}}.$$

The authors in [9] use also cross layer QoS metrics, evaluated with the ITU E-model for path selection. However, this work can only be applied for VoIP traffic, as the E-model rates only voice quality.

The authors in [10] do not use the common RTT calculation as metric for path quality estimation because the acknowledgements may return from a different path. Also they suggest that the calculation of RTT for every packet can not reflect the RTT variation process and estimate the trend of path quality. Hence, they propose to divide the total time of sending data into dissimilar periods in terms of the sending situation and calculate the quality metric for each of these periods as follows.

$$Q = \frac{T_l - T_e}{\text{buffersize}},$$

where T_e is the timestamp for the first packet send in that period, T_l is the timestamp for the last acknowledgement and bufersize is the allocated buffer size for that period. Using this metric and confidence intervals for selecting the sampling periods, they developed their proposed data distribution scheduler.

III. Analytical Model of SCTP

The previous section examined several SCTP enhancements to the multi-homing support for dynamic interface selection. However, all of them are evaluated through simulations in limited and some cases biased scenarios. Analytical modelling assists to evaluate the theoretical performance of a system. In this section we model the throughput of a modified SCTP protocol, which switches between primary and secondary paths not only based on time-out event as in the original SCTP specifications, but using a utility function, as presented in section II, such as minimum RTT [4], [5].

A. Original SCTP modelling

There are two published papers to the best of our knowledge in the literature that provide analytical model for SCTP throughput based on discrete Markov chain models. The work presented in [11] models SCTP with original multihoming functionality, where primary and secondary paths are alternated only at loss events as seen in Markov chain diagram in Fig. 1. Each state has three elements $\{cwnd, W_t, l\}$, where $cwnd$ represents the congestion window size in segments, W_t represents the slow start threshold and l is an indicator of loss. The transitions are grouped in five categories as summarized below[3]:

- **Slow Start**: from state $\{w, W_t, 0\}$ to $\{2w, W_t, 0\}$ with probability $P_w(0)$,
- **Congestion Avoidance** from state $\{w, W_t, 0\}$ to $\{w + 1, W_t, 0\}$ with probability $P_w(0)$,
- **Time-out** from state $\{w, W_t, 0\}$ to $\{0, \lfloor w/2 \rfloor, 1\}$ with probability P_w^{TO},
- **Exponential Backoff** from state $\{0, W_t, 1\}$ to $\{0, 2, 1\}$ with probability $P_1(1)$, and
- **Fast Retransmission** from state $\{w, W_t, 0\}$ to $\{\lfloor w/2 \rfloor, \lfloor w/2 \rfloor, 1\}$ with probability P_w^{FR}.

$P_w(j)$ represents the probability of j segments being lost in a window size w. P_w^{TO} and P_w^{FR} represent the probability of a Time Out (TO) or a Fast Retransmission (FR) event occurs when $cwnd = w$, respectively.

This model calculates the expected number of segments generated per RTT as:

$$G = \sum_{w=1}^{wmax} wP(cwnd^{(w)}), \tag{1}$$

[2]The Ideal scheduler is simply the sum of the bandwidth of the two paths.

[3]For more information and notations on the equations please refer to [11]

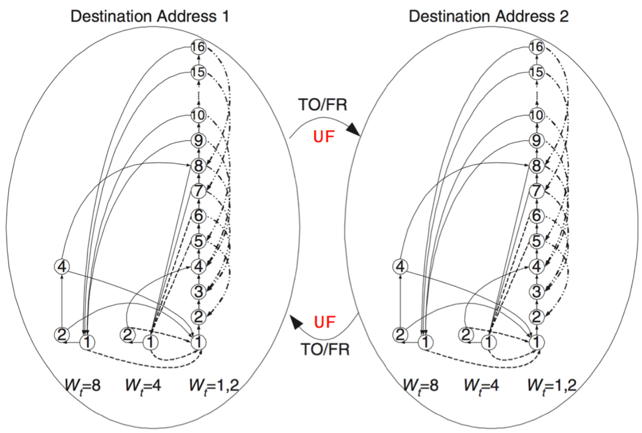

Fig. 1: SCTP Markov Chain state transition diagram with multihoming. NOTE: UF events only in modified SCTP model.

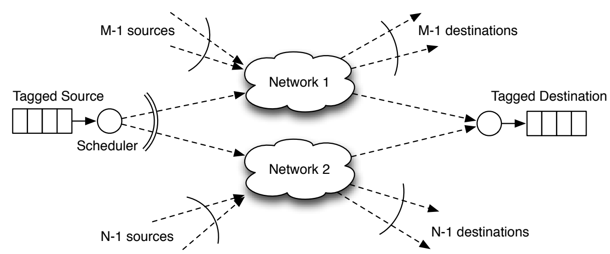

Fig. 2: Network model.

where by solving the Markov model in steady state the probability of congestion window $cwnd = w$ is given by

$$P(cwnd^{(w)}) = \sum_{W_t=2}^{wmax} \sum_{l=0}^{1} \pi(w, W_t, l). \tag{2}$$

Finally, the expected lost segments from the primary path, i.e. traffic transferred into the secondary can be calculated by

$$E[L] = \sum_{w=1}^{wmax} \sum_{k=1}^{wmax} kP(loss^{(k)} \mid ccwnd^{(w)})P(ccwnd^{(w)}), \tag{3}$$

where $P(loss^{(k)})$ represents the probability that k segments are lost during the last state transition, with the current congestion window $ccwnd = w$.

The second work that developed an analytical model of SCTP is presented in [12]. However, the proposed model does not consider the multi-homing functionality, while trying to provide higher accuracy in the steady-state throughput. It models the different states of a SCTP association, namely congestion avoidance (CA), exponential back-off (EB) after time-outs (TO) and slow-start (SS). For each state, it estimates the number of packets and duration in steady state and calculates the throughput.

Nevertheless, both these models assume the default SCTP multi-homing operation. In section II we presented SCTP enhancements, in which the selection of primary and secondary path is dynamic, based on some short of utility function. The transition from primary to secondary is not triggered only by a TO/FR event, but also by the utility function (UF) event.

B. Modified SCTP model

This subsection presents the modified SCTP model that takes into consideration the minimum RTT to select primary path. Our work is based on the SCTP model in [11], however we extend the state transition shown in Fig. 1 with the addition of Utility Function (UF) event. The state transition for UF from $(w, W_t, 0)$ to $(w, W_t, 2)$ is with probability P^{UF}. Our objective is to quantify P^{UF}; the probability that according to the utility function there is a swap of primary and secondary path.

1) Definition of P^{UF}: According to our utility function, a UF event happens when the RTT of Network 1 is larger than that of Network 2 assuming that the current primary path is on Network 1, and vice versa. This is formulated for N_x, N_y the two networks in (4), where θ is the RTT time.

$$P^{UF}_{N_x} = P\{\theta_{N_x} > \theta_{N_y} \mid N_x \text{ is primary}\}. \tag{4}$$

From Bayes formula we have:

$$P\{\theta_{N_x} > \theta_{N_y} \mid N_x\} = \frac{P\{N_x \mid \theta_{N_x} > \theta_{N_y}\}P\{\theta_{N_x} > \theta_{N_y}\}}{P\{N_x\}}, \tag{5}$$

Now we need to estimate the RTT for each path. This results from the analysis of the *network model* as represented in Fig. 2 and is the sum of queueing delay (d_q) and propagation delay (d_t). Assuming that each individual network can be modelled as a M/M/1/K queue, similar to [11], with a fixed capacity BW and queue size K, we can calculate its queueing delay using *Little's Law*. Propagation delay can be assumed fixed and depended on the network technology used.

2) Queueing Delay Calculation: Assuming that each source i has a traffic flow $\lambda_{i,k}$ on network κ and there are N and M flows on each network, the total traffic flow on each network is $\lambda_\kappa = \sum_{i=0}^{k} \lambda_{i,\kappa}$ with $k \in \{M, N\}$ and $\kappa \in \{N_1, N_2\}$. Aggregation of a large number of SCTP traffic sources results in the overall traffic arrival to the network being Poisson. To find the average queueing delay ($d_{q,\kappa}$) in a network we use *Little's Law* and evaluate it as follows:

$$d_{q,\kappa} = \frac{S_\kappa}{\lambda_\kappa}, \tag{6}$$

where S_κ is the amount of packets in the queue for network κ given by:

$$S_\kappa = \begin{cases} \frac{K}{2} & \rho = 1 \\ \frac{\rho}{1-\rho} - \frac{K+1}{1-\rho^{(K+1)}}\rho^{(K+1)} & \rho \neq 1 \end{cases}, \tag{7}$$

and $\rho = \lambda_\kappa/\mu_\kappa$, $\mu_\kappa = (BW_\kappa/8)PacketSize$. Finally, RTT on Network 1 is calculated as $\theta_{N_1} = d_{q,N_1} + d_{t,N_1}$. In a similar way, we can estimate the RTT of the second network, and finally find the probability $\theta_{N_1} > \theta_{N_2}$.

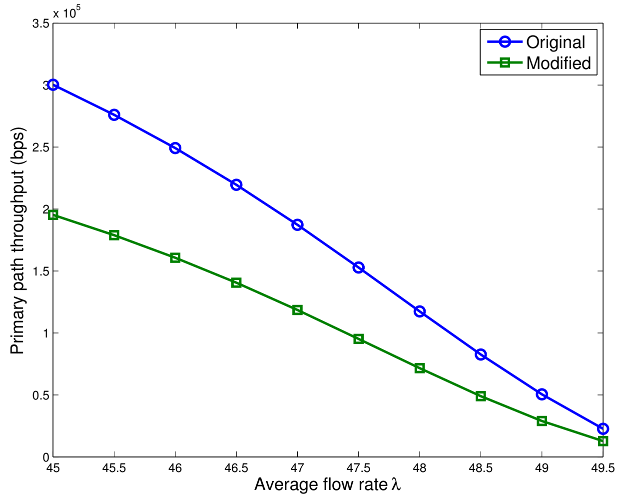

Fig. 3: Primary path throughput.

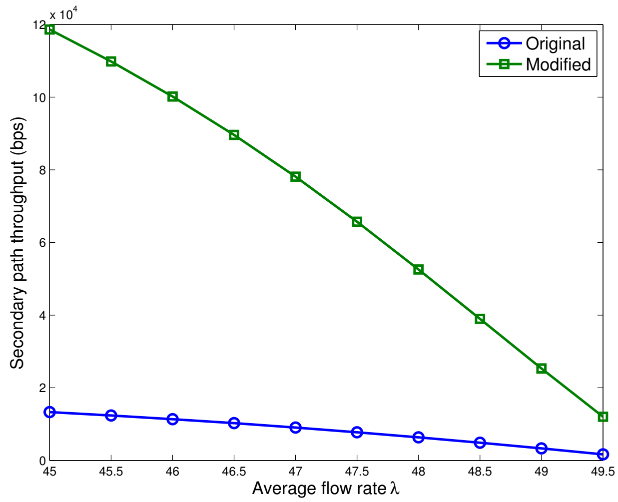

Fig. 4: Secondary path throughput.

IV. Evaluation

In this section we evaluate the proposed model and compare it with [11] on throughput per path. For the evaluation of the proposed model we used the following parameters: $wmax = 32$, capacity 100 MBps, queue size K=50, segment size 500 bytes, number of flows on each network 50, propagation delay 0.1 sec and we varied the flow rate λ.

As we observe in Fig. 3 and 4, throughput is decreased as average flow rate is increased. This is due to the congestion and increase of segment loss probability. In addition, since queueing delay is increased, RTT is increased, which also has negative impact on throughput. While the total throughput in the two cases (original and modified) remains the same, the distribution of traffic among the available paths is different. The modified SCTP utilizes the secondary path more frequently as it can be seen in Fig. 5. When flow rate reaches the limit of path capacity, both paths are equally utilised.

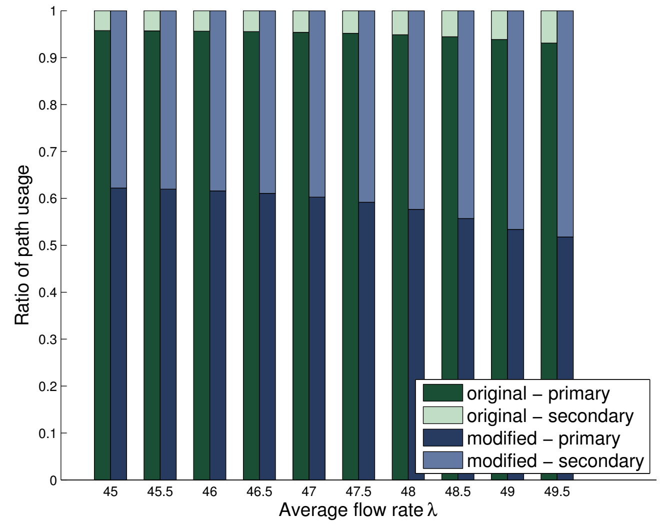

Fig. 5: Path usage ratio.

V. Conclusion

Since original SCTP multi-homing functionality is only used when primary address becomes unavailable, none of the previous SCTP analytical models are applicable for dynamic interface switching. There are proposals for different utility functions, such as minimum RTT or maximum bandwidth, to dynamically switch interfaces. However they are only evaluated through simulations in limited scenarios. Hence, we develop an analytical model for a multi-homed SCTP association, which considers minimum RTT, and compare it with the original SCTP model. Future work on this subject would evaluate other utility functions such as those reviewed in section II. Further investigation on the effect of mobility and connectivity in vehicular networks is required and incorporated in the model.

References

[1] A. Vinel, "3GPP LTE Versus IEEE 802.11p/WAVE: Which Technology is Able to Support Cooperative Vehicular Safety Applications?" *IEEE Wireless Communications Letters*, vol. 1, no. 2, pp. 125–128, 2012.

[2] ETSI, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions," European Telecommunications Standards Institute (ETSI), TR 102 638, 2009.

[3] R. Stewart, "Stream Control Transmission Protocol," RFC 4960 (Proposed Standard), Internet Engineering Task Force, Sep. 2007, updated by RFCs 6096, 6335, 7053.

[4] S. Kashihara, T. Nishiyama, K. Iida, H. Koga, Y. Kadobayashi, and S. Yamaguchi, "Path selection using active measurement in multi-homed wireless networks," in *International Symposium on Applications and the Internet*, 2004, pp. 273–276.

[5] X. Hou, P. Deshpande, and S. Das, "Moving bits from 3G to metro-scale WiFi for vehicular network access: An integrated transport layer solution," in *IEEE International Conference on Network Protocols (ICNP)*, 2011, pp. 353–362.

[6] J. Iyengar, P. Amer, and R. Stewart, "Concurrent Multipath Transfer Using SCTP Multihoming Over Independent End-to-End Paths," *IEEE/ACM Transactions on Networking*, vol. 14, no. 5, pp. 951–964, 2006.

[7] R. Fracchia, C. Casetti, C. Chiasserini, and M. Meo, "Wise: Best-path selection in wireless multihoming environments," *IEEE Transactions on Mobile Computing*, vol. 6, no. 10, pp. 1130–1141, 2007.

[8] Y. Cao, C. Xu, J. Guan, J. Zhao, and H. Zhang, "Cross-layer cognitive cmt for efficient multimedia distribution over multi-homed wireless networks," in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2013, pp. 4522–4527.

[9] J. Fitzpatrick, S. Murphy, M. Atiquzzaman, and J. Murphy, "Using cross-layer metrics to improve the performance of end-to-end handover mechanisms," *Comput. Commun.*, vol. 32, no. 15, pp. 1600–1612, 2009.

[10] C. Xu, T. Liu, J. Guan, H. Zhang, and G.-M. Muntean, "CMT-QA: Quality-Aware Adaptive Concurrent Multipath Data Transfer in Heterogeneous Wireless Networks," *IEEE Transactions on Mobile Computing*, vol. 12, no. 11, pp. 2193–2205, 2013.

[11] S. Fu and M. Atiquzzaman, "Performance modeling of sctp multihoming," in *IEEE Global Telecommunications Conference, GLOBECOM '05*, vol. 2, Nov 2005, pp. 786–791.

[12] T. D. Wallace and A. Shami, "An analytic model for the stream control transmission protocol," in *IEEE Global Telecommunications Conference. GLOBECOM '10*, 2010, pp. 1–5.