Research Article

Disorder Analytic Model-Based CMT Algorithms in Vehicular Sensor Networks

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Recently, vehicular sensor networks (VSNs) have emerged as a new intelligent transport networking paradigm in the Internet of Things. By sensing, collecting, and delivering traffic-related information, VSNs can significantly improve both driving experience and traffic flow control, especially in constrained urban environments. Latest technological advances enable vehicular devices to be equipped with multiple wireless interfaces, which can support cooperative communications for concurrent multipath transfer (CMT) in VSNs. However, path heterogeneity and vehicle mobility cause CMT not to achieve the same high transport efficiency recorded in wired nonmobile network environments. This paper proposes a novel vehicular network-based CMT solution (VN-CMT) to address the above issues and improve data delivery efficiency. VN-CMT is based on a CMT disorder analytic model which can effectively and accurately evaluate the degree of out-of-order data. Based on this proposed model, a series of mechanisms are introduced as follows: (1) a packet disorder-reducing retransmission policy to reduce retransmission delay; (2) a path group selection algorithm to find the best path set for data multipath concurrent transfer; and (3) a data scheduling mechanism to distribute data according to each path's capacity. Simulation results show how VN-CMT improves data delivery efficiency in comparison with an existing state-of-the-art solution.

1. Introduction

Vehicular sensor networks (VSNs) are expected to be at the centre of one of the major new application areas for intelligent transport systems [1, 2] in the Internet of Things (IoT) world. Unlike most of the nodes in other wireless sensor networks [3, 4], in VSNs vehicles can be equipped easily with large-capacity-storage and powerful-computing devices. This offers the opportunity to deploy a broad range of innovative solutions, including peer-to-peer content sharing [5, 6], quality-oriented multimedia content delivery [7, 8], user-personalised multimedia content delivery [9], energy-aware traffic management solutions [10], and traffic information dissemination applications [11]. These applications are designed to improve safety, traffic management, navigation, and user convenience. Additionally we are witnessing extensive developments in the area of wireless access technologies in VSNs. Vehicles can carry multiple types of wireless interfaces, and they can interact with each other and access the Internet via several communication technologies such as IEEE 802.11p, 3G/4G, and WiMAX [12].

Transport protocols play an increasingly important role in IoT to comply with the emerging new devices and applications and support efficient data transmissions. The Stream Control Transmission Protocol (SCTP) [13] is a new multihoming-based transport layer protocol. It has been widely used in vehicular networks for the support of concurrent multipath transfer (CMT) [14]. Viewed as

support to reliable and high-throughput services by utilizing several paths to transmit data packets concurrently, CMT can achieve good level of bandwidth aggregation [15]. Figure 1 illustrates CMT usage in a heterogeneous VSN environment. It shows how a vehicle can concurrently use both 3G and 802.11p (WAVE) access links to communicate with the server through the Internet. This approach significantly improves data transmission efficiency in VSNs.

Unfortunately, as vehicles move rapidly, intervehicle connections are always broken and reestablished. This problem leads to frequent change of network topology, which means continual variation of round trip time (RTT) and loss rate in the transport layer. In CMT, paths having similar and stable bandwidth, delays, and loss rates are prerequisites for good data delivery performance. When the conditions of heterogeneous paths are very different and keep changing, packet disorder at the receiver side becomes serious. Since the receive buffer is finite, frequent disorderly arrived packets will lead to receiving buffer-blocking issue that drastically decreases CMT performance. Recently, some research work [16] has been proposed to improve delivery performance by reducing reordering. However, to the best of our knowledge, there are no proposed CMT disorder analytic models which can effectively and accurately investigate the characteristics of out-of-order data and then optimize the CMT-related algorithms.

In this paper, we introduce an efficient analytic model for CMT disorder in intelligent transport systems. This model derives a function of bandwidth, RTT, and loss rate, which can accurately compute the degree of data disorder. Based on this model, we propose novel path group selection algorithm, data scheduling scheme, and retransmission policy for concurrent multipath transfer over VSNs in order to reduce reordering and improve data delivery performance. These were integrated into a newly designed solution vehicle network-CMT (VN-CMT) which was evaluated by simulations in comparison with an existing state-of-the-art method.

2. Related Work

Many researchers focus on exploiting SCTP features to support efficient CMT. Dreibholz et al. [17] investigated the ongoing SCTP standardization progress in the IETF and gave an overview of activities and challenges in the areas of CMT and security. Shailendra et al. [18] proposed the MPSCTP protocol which enhances the basic SCTP. MPSCTP changed the SCTP header structure and introduced newly designed algorithms to provide greater reliability during concurrent multipath usage. Kim et al. [19] introduced a modification of SACK handling in CMT to prevent a SCTP sender from updating the congestion control window size when availability of the path is ambiguous. We previously proposed a novel realistic evaluation tool set [20–22] to analyze and optimize the performance of multimedia distribution when making use of a CMT-based multihoming SCTP approach. SCTP CMT is currently in the discussion of standardization within the IETF [15].

In recent years, increasing number of researchers are using the promising SCTP in both vehicular networks and wireless sensor networks. Lu and Wu [23] adopted SNMP and SIP over SCTP as network management protocols and evaluated their behaviors in wireless sensor networks. Kim and Lee [24] proposed a Mobile Stream Control Transmission Protocol- (MSCTP-) based handover scheme for vehicular networks which seamlessly adapts to different delivery conditions. Unfortunately, both of these works did not take into account any of the benefits brought by CMT. Huang and Lin [25] proposed a fast retransmission solution enabled by the use of relay gateways for CMT (RG-CMT) in vehicular networks. When packets are lost due to error or handoff loss in the wireless link, RG-CMT can retransmit lost packets fast from the relay gateway to the vehicle, which enables achieving higher throughput than the basic CMT.

However, there is still significant ongoing work addressing many challenges of the SCTP CMT. The SCTP CMT strategy makes use of a round-robin scheduling to distribute data packets via different independent network interfaces to utilize the aggregated bandwidth. However this "blind" round-robin scheme sends the packets to all available multiple paths equally without considering their different communication conditions such as bandwidth and delay. As a result, CMT will lead to serious out-of-order data chunks for reordering. It causes even more serious concerns in vehicular sensor networks, as in VSNs the asymmetric paths with different quality characteristics are more common and sensitive to variations than in wired networks. Consequently, CMT often suffers from significant receiver buffer-blocking problems, which degrades transmission efficiency and network utilization.

3. VN-CMT Disorder Analytic Model

We define the degree of data disorder as the distance between packets' sending order and their receiving order. The disorder degree can be estimated through the *Euclidean distance algorithm* as follows:

$$\sqrt{\sum_{a=1}^{N} \left| X_a^r - X_a^s \right|^2}, \tag{1}$$

where N represents the number of packets transmitted during a data distribution time. X_a^r denotes packet X_a's receiving order, and X_a^s represents X_a's sending order in the series of N packets. $X_a^r - X_a^s$ is the packet order gap for X_a during the N packet delivery.

The average packet gap in path i can be estimated by the average gap for packets transmitted on this path times the number of packets sent on path i. We assume that the N packets are transmitted over n paths concurrently. The total packet gap in the given data distribution time can be computed by (2) and is the sum of packet gaps computed on every path:

$$\sqrt{\sum_{i=1}^{n} \left(avGap_i \right)^2 \times \text{num}Pkts_i}, \tag{2}$$
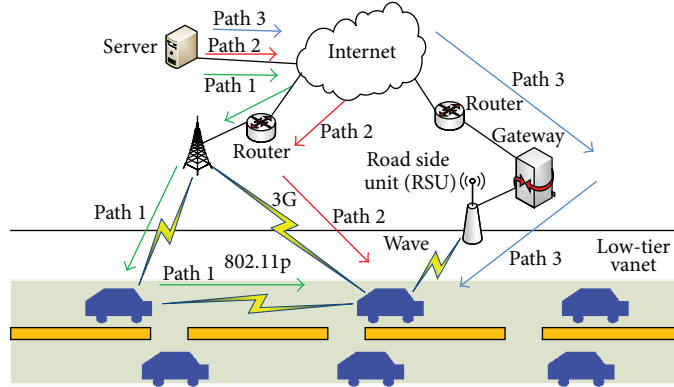
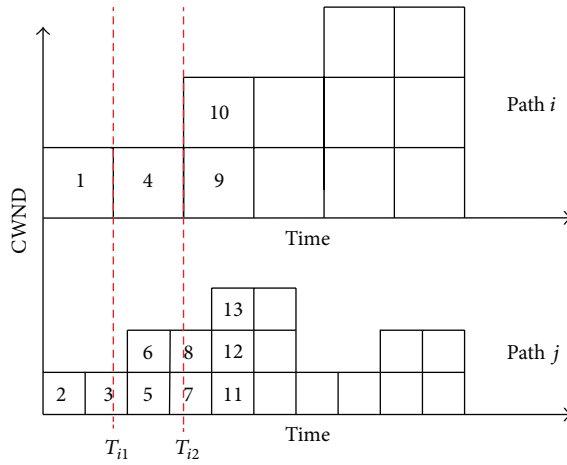FIGURE 1: Concurrent multipath transfer in vehicle sensor networks.

FIGURE 2: Model of packet gap.

where n is the number of paths used in this data distribution, $numPkts_i$ represents the numbers of packets sent over path i, and $avGap_i$ denotes the average gap of the $numPkts_i$ packets which occurs in path i.

We consider two situations to derive $avGap_i$. First we calculate the average gap of the packets which are sent successfully over path i. In this case, the gap is mainly brought by transmission delay and is denoted as $avOnetran_i$. Then, we consider the average packet gap caused by packet loss and is expressed as $avRetran_i$. So $avGap_i$ can be computed by the following:

$$avGap_i = avOnetran_i \times (1 - p_i) + avRetran_i \times p_i, \quad (3)$$

where p_i is the loss rate of path i. Next, $avOnetran_i$ is derived. As Figure 2 illustrates, we model the congestion avoidance behavior of SCTP in terms of "rounds." A round starts with transmission of all the packets in current CWND. Then no other packets are permitted to be sent until one of those packets is ACKed. We assume that packet 4 is sent at time T_{i1} and gets to the ACK at time T_{i2} over path i, then the possible gap contribution of packet 4 can be regarded as the number

of packets which are sent over other paths (Figure 2 illustrates only one other path j for instance) after T_{i1} and received successfully before T_{i2}. For any path j, the packets sent after T_{i1} and received successfully before T_{i2} can be estimated by average number of rounds that occur between T_{i1} and T_{i2} times the average size of CWND. The $avOnetran_i$ can be calculated by

$$avOnetran_i = \sum_{j=1\&\&j\neq i}^{n} f\left(\frac{\text{RTT}_i}{\text{RTT}_j} - 1\right) E_j[C], \quad (4)$$

where $E_j[C]$ is the average CWND of path j. $f(x)$ equals 0 if x is less than 0. Otherwise, $f(x)$ equals x. $f(\text{RTT}_i/\text{RTT}_j - 1)$ represents the average rounds that occurred in path j during a round in path i. In order to get $E_j[C]$, we can use the results in [26] by (5), as SCTP behaves almost the same as TCP on single path:

$$E_j[C] = \sqrt{\frac{8(1 - p_j)}{3bp_j} + \frac{(3b-2)^2}{9b^2}} - \frac{3b-2}{3b}, \quad (5)$$

where p_j is the loss rate of path j. b is the number of packets that are acknowledged by a received ACK. As SCTP follows the delayed acknowledgement algorithm specified in RFC 2581 in which a receiver normally sends one cumulative ACK for two consecutive packets received [13], (5) can be simplified to (6) with $b = 2$:

$$E_j[C] = \frac{2}{3} \times \left(\sqrt{\frac{3}{p_j} - 2} - 1\right). \quad (6)$$

From (4) and (6), (7) can be deduced as the following:

$$avOnetran_i = \frac{2}{3} \sum_{j=1\&\&j\neq i}^{n} f\left(\frac{\text{RTT}_i}{\text{RTT}_j} - 1\right) \times \left(\sqrt{\frac{3}{p_j} - 2} - 1\right). \quad (7)$$

Next, we start to derive $avRetran_i$. $avRetran_i$ can be deemed in principle as the average number of sent and received packets in the paths excluding path i during the loss-detection period plus the average number of transferred

packets in the paths excluding the retransmission path during retransmission period. As packets will be ACKed in a round, the loss of packets will be detected by fast retransmission mechanisms in a round and retransmits in a path determined by the retransmission policy. We first introduce a novel packet disorder-reducing retransmission policy and then continue to discuss $avRetran_i$ for modeling.

3.1. Packet Disorder-Reducing Retransmission Policy.

A preferable retransmission policy accelerates retransmissions in order to reduce packet disorder, namely, can make the average retransmission time shorter. In SCTP, the recommended CMT retransmission policies are RTX-CWND and RTX-SSTHRESH. Equation (6) shows how the average CWND is mainly decided by loss rate. The smaller the loss rate is, the larger the average CWND is. As SSTHRESH always changes when packets are lost, it is also decided by loss rate. It is obvious that preferred packet retransmission is on the path with the lowest loss rate. In our model, besides loss rate, RTT is also considered as an important factor for retransmission. Smaller RTT means smaller packet gaps on this path and smaller gaps indicate less reordering. Considering those two factors, a path having smaller $RTT/(1 - p)$ is more likely to retransmit packets quickly and successfully. However, unlike the average loss rate, the current real-time loss rate is difficult to get accurately in VSNs. However, current CWND is easily obtained, and, as mentioned above, there is a direct relationship between CWND and loss rate; we use instead of loss rate p current CWND, namely, $p = 1/\text{CWND}$. By making use of $RTT/(1 - p)$, (8) shows the formula employed for evaluating the retransmission path quality as follows:

$$Q = \frac{\text{RTT}}{1 - (1/\text{CWND})}. \tag{8}$$

The packet disorder-reducing retransmission policy is based on the fact that the path with the smallest Q value is chosen as the packet retransmission path. Algorithm 1 describes the retransmission strategy.

Assuming that the retransmission path is path x, then the $avRetran_i$ can be obtained according to the following:

$$avRetran_i = avLostDetection_i + avRetranGap_x. \tag{9}$$

As the lost detection and transmitting a packet successfully on path i both perform in one round (10) can be written as follows:

$$avLostDetection_i = avOnetran_i. \tag{10}$$

Similarly, (7) is derived and the formula for computing $avRetranGap_x$ presented in (11) is obtained as follows:

$$avRetranGap_x = \frac{2}{3} \sum_{j=1\&\&j \neq x}^{n} f\left(\frac{\text{RTT}_x}{\text{RTT}_j} - 1\right) \\ \times \left(\sqrt{\frac{3}{p_j} - 2} - 1\right) \times A_x, \tag{11}$$

where A_x is the average retransmission times of a packet in path x. Assuming that a packet retransmits k times until it is transferred successfully, then A_x can be calculated by the following:

$$A_x = \sum_{k=1}^{\infty} \left[p_x^{k-1} (1 - p_x) k \right] = \frac{1}{1 - p_x}. \tag{12}$$

By combining (11) and (12), (13) can be deduced as follows:

$$avRetranGap_x = \frac{2}{3} \sum_{j=1\&\&j \neq x}^{n} \left[f\left(\frac{\text{RTT}_x}{\text{RTT}_j} - 1\right) \\ \times \left(\sqrt{\frac{3}{p_j} - 2} - 1\right) \times \frac{1}{1 - p_x} \right]. \tag{13}$$

By following (3), (7), (9), (10), and (13), the total gap of a packet sent on path i can be computed as follows:

$$avGap_i = \frac{2}{3} \sum_{j=1\&\&j \neq i}^{n} \left[f\left(\frac{\text{RTT}_i}{\text{RTT}_j} - 1\right) \times \left(\sqrt{\frac{3}{p_j} - 2} - 1\right) \right] \\ + \frac{2}{3} \sum_{j=1\&\&j \neq x}^{n} \left[f\left(\frac{\text{RTT}_x}{\text{RTT}_j} - 1\right) \times \left(\sqrt{\frac{3}{p_j} - 2} - 1\right) \right. \\ \left. \times \frac{1}{1 - p_x} \right] \times p_i. \tag{14}$$

We have derived the average gap of a packet sent on path i. Next, we employ the path i's bandwidth denoted as B_i to weight it; namely, we replace $numPkts_i$ with B_i in (2), then the disorderly degree (defined as D) for a path group having n paths for CMT can be computed by (15), making use of formulas (2) and (14) as follows:

$$D = \sqrt{\sum_{i=1}^{n} \left[(avGap_i)^2 \times B_i \right]}. \tag{15}$$

D characterizes the disorderly degree of a path group. Large D value will influence the throughput. This proposed disorder analytic model captures the essence of packet disorder in CMT. Based on the model and taking D into account, we can design and optimize CMT-related algorithms, such as the above proposed retransmission policy and also path group selection and data scheduling algorithms to reduce packet disorder and increase CMT throughput.

3.2. Packet Disorder-Reducing Path Group Selection Algorithm.

As mentioned above, in VSNs, frequent break and reestablishment of connections lead to often changes in paths' conditions. Making use of bad paths will cause serious out-of-order data deliveries. So, good path group selection algorithms are required to find a good path group for concurrent data transmissions in dynamic wireless environments. We

```
(1)  //Let mPathset be a path set used for data concurrent transfer;
(2)  //count(mPathset) returns the size (number of paths) of the set mPathset;
(3)  if (a packet Pkt needs retransmission)
(4)      Q = ∞;
(5)      for (i = 0; i ≤ count(mPathset); i + +)
(6)          obtain mPathset[i]'s RTTᵢ and current cwndᵢ;
(7)          Qᵢ = RTTᵢ/(1 − (1/cwndᵢ));
(8)          if (Qᵢ < Q)
(9)              Q = Qᵢ; j = i;
(10)         end if;
(11)     end for;
(12) end if;
(13) retransmit the packet Pkt over the path mPathset[j] as soon as possible;
```

ALGORITHM 1: Packet disorder-reducing retransmission policy.

aim to make the selected paths in the path group have similar communication quality in order to reduce received data reordering and alleviate receiver buffer blocking. Two factors, namely, disorder degree D and total bandwidth are considered in our packet disorder-reducing path group selection algorithm. The disorder degree is expected to be small, while the total bandwidth is expected to be large. These two parameters are employed to compute a new parameter σ to evaluate a path group (set) as the following:

$$\sigma_s = B_{\text{total}}^s \times \left(1 - \frac{D_s}{\sum_{j=1}^{M} D_j} \right), \tag{16}$$

where B_{total}^s and D_s represent the total bandwidth and the disorder degree for a path set s, respectively. We assume that there are M possible combinations of path sets. $\sum_{j=1}^{M} D_j$ computes the M path sets' total disorder degree. σ_s is used to evaluate the throughput of the path set s; the larger σ is, the better performance the path group will achieve. The proposed path group selection algorithms aim is to find a path set with the largest σ for concurrent data transmissions. Algorithm 2 reveals the details of the process of a path group selection.

3.3. Packet Disorder-Reducing Data Scheduling Algorithm. The data scheduling algorithm of standard CMT uses a "blind" round-robin strategy. It splits SCTP packets over all available paths in an equal-share way without considering various path quality differences. This method is simple but not reasonable and can cause many out-of-order data packet deliveries. Hence, a better algorithm is required. To reduce the disorder, the smaller a packet TSN is, the earlier the packet should arrive successfully at receiver. Namely, the smallest TSN packet should be sent over the path whose gap is the smallest possible one. In formula (14), we have derived a function to compute the average gap of a path. So, we propose packet disorder-reducing data scheduling algorithm as follows: any packet is sent on the path whose average gap is the smallest and its CWND allows transmission. By using this simple, but highly efficient, path data scheduling algorithm, the disorder is significantly reduced and data

delivery performance is greatly improved. The above process is detailed in Algorithm 3.

4. Application and Performance Evaluation

In this section, we first give an example application scenario for the disorder analytic model-based CMT algorithms in vehicular sensor networks, then we evaluate the proposed VN-CMT strategy and compare its performance with the basic CMT of SCTP by making use of the network simulator (NS-2.35) [27] in a realistic application scenario.

4.1. Application Scenario. Lately, many cities around the world have witnessed large-scale deployment of traffic-related mobile TV broadcasting services. For example, following the Beijing Olympics, almost all taxis (out of the over 700 thousand vehicles in the Chinese capital city) are equipped with on-board equipment which supports traffic TV broadcasting signal retrieval and multimedia playback. Additionally, we are witnessing extensive developments in wireless access technologies including WiFi, LTE, LTE-A, and WiMAX and especially in vehicular wireless technologies such as Wireless Access in the Vehicular Environment (WAVE) (IEEE 802.11p), enabling data delivery via vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-road-side-unit (V2R) communications. This paves the way towards multihomed wireless networks, where vehicles in vehicular networks can be equipped with multiple wireless interfaces. Each vehicle can establish multiple connections with other vehicles or servers across different networks and distribute data employing concurrent multipath transfer mechanism. Figure 3 illustrates the application scenario which follows our previous work [28]. Vehicle A can download the real-time traffic video, that it interests from traffic information server through WiFi, LTE(3G/4G), and 802.11p network concurrently. It can aggregate bandwidth and accelerate video downloading speed to ensure the traffic video playback smoothly and timely. The driver can promptly adjust his driving route in terms of the viewed traffic information, which significantly improves both driving experience and traffic flow control.

```
(1)   //Let mPathGroup be all the possible combinations of path sets;
(2)   //count(X) returns the size of X; mPathset denotes a path set;
(3)   D_total = 0; /* D_total denotes the total disorder degree of all path groups */
(4)   for (i = 0; i ≤ count(mPathGroup); i + +)
(5)       get the path set mPathGroup[i]'s disorder degree D_i by (15);
(6)       D_total = D_total + D_j;
(7)   end for;
(8)   σ = 0;
(9)   for (i = 0; i ≤ count(mPathGroup); i + +)
(10)      mPathset = mPathGroup[i];
(11)      B_total^{mPathset} = 0;
(12)      /* B_total^{mPathset} represents the total bandwidth of all paths in mPathset*/
(13)      for (j = 0; j ≤ count(mPathset); j + +)
(14)          obtain the path mPathset[j]'s bandwidth B_{mPathset[j]};
(15)          B_total^{mPathset} = B_total^{mPathset} + B_{mPathset[j]};
(16)      end for;
(17)      obtain the path set mPathset's disorder degree D_{mPathset} by (15);
(18)      σ_{mPathset} = B_total^{mPathset} × (1 − (D_{mPathset}/D_total));
(19)      if (σ_{mPathset} > σ)
(20)          σ = σ_{mPathset}; g = i;
(21)      end if;
(22)  end for;
(22)  mPathGroup[g] is selected as the path set for data concurrent transfer;
```

ALGORITHM 2: Packet disorder-reducing path group selection algorithm.

```
(1)   //Let mPathset be a path set used for data concurrent transfer;
(2)   //count(mPathset) returns the size of the set mPathset;
(3)   if (a packet Pkt needs transmission)
(4)       for (i = 0; i ≤ count(mPathset); i + +)
(5)           compute the path mPathset[i]'s gap avGap_i by (14);
(6)       end for;
(7)       sort items in mPathset[i] in ascending order of the avGap value;
(8)       for (j = 0; j ≤ count(mPathset); j + +)
(9)           if (mPathset[j]'s CWND allows transmission)
(10)              transmit the packet Pkt on the path mPathset[j];
(11)              break;
(12)          end if;
(13)      end for;
(14)  end if;
```

ALGORITHM 3: Packet disorder-reducing data scheduling algorithm.

4.2. Performance Evaluation. VN-CMT's performance is assessed in comparison with the basic CMT of SCTP in an application scenario of the traffic real-time TV broadcasting system as presented in Figure 3. We have implemented our VN-CMT by modifying the NS2 standard CMT module accordingly. Figure 4 illustrates the simulation network topology which is described in terms of Figure 3 application scenario. Two endpoints, namely, Sender and Receiver,

communicate through three paths which denote WiFi, LTE, and 802.11p connections, respectively and having different bandwidths. $R_{11}, R_{12}, \ldots, R_{32}$ are routers. The RTX-CWND is used as the default retransmission policy for standard CMT. The default receive buffer size is set to 64 KB. The link queue limit and type are set 50 packets and Droptail, respectively. The RTT and loss rate of each path are varied simulating dynamic network environments. The bandwidth, loss rate
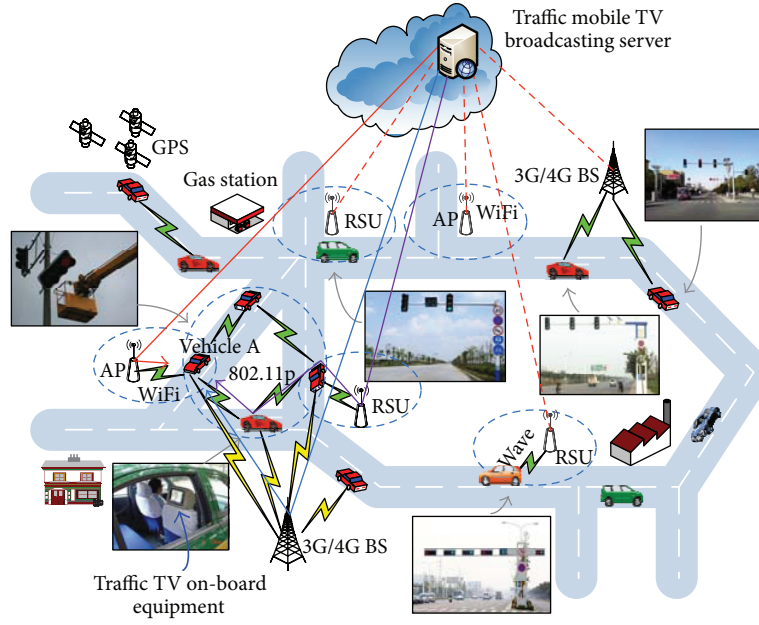
FIGURE 3: A application scenario of traffic mobile TV broadcasting services.

and RTT values are set to comply with the characteristics of WiFi, LTE, and 802.11p networks, respectively. For instance, LTE is a cellular network and is more stable than WiFi and 802.11p, so the the loss rate variation range of LTE is set to [0.01 0.02] which is less than the [0.01 0.1] range of WiFi and the [0.1 0.2] range of 802.11p. Due to vehicles' mobility, the V2V connections in 802.11p network easily become disconnected, so the loss rate of 802.11p is set worse than those for WiFi and LTE. Similar to the loss rate, the bandwidth and RTT are set to reasonable values corresponding to WiFi, LTE and 802.11p connections, respectively (as shown in Figure 4). The other parameters use the SCTP default values. The simulation time is 140 s and the application traffic is sent by the Sender with an infinite data flow.

(1) *Out-of-order packets*: Figure 5 shows a comparison of out-of-order chunks among CMT and VN-CMT. The out-of-order TSN metric used in this experiment is measured by the offset between the TSNs of two consecutively received data chunks (the difference between the TSN of the current data chunk and that of the latest received data chunk). The out-of-order TSN metric portrays the characteristics of concurrent data transmission over multiple paths. The figure presents the out-of-order TSN metric variation between simulation times $t = 20$ s and $t = 21$ s, which is representative for the whole simulation results. As the figure shows, CMT generates more out-of-order chunks and requires increased reordering than VN-CMT. The peak out-of-order data reception at the receiver is approximately 60 using CMT, while it is only 20 when using VN-CMT, which is proposed in this paper.

(2) *Packet sending and receiving times*: Figures 6 and 7 illustrate the sending and arrival times of several data packets when CMT and VN-CMT schemes are used, respectively. In order to better illustrate the comparison, the results between $t = 20$ s and 21 s are presented only (part of the congestion avoidance stage). The TSNs of these data packets growth have three main slopes in CMT and two main slopes in VN-CMT. The top slope in Figure 6 represents data flows over path 2 in CMT. The middle one in Figure 6 and the top one in Figure 7 denote data flows over path 3 in CMT and VN-CMT, respectively. The lowest slopes in Figures 6 and 7 represent data flows over path 1 in both CMT and VN-CMT. In CMT, the sender uses the round-robin method to transmit data chunks over all the paths equally, without considering the path quality differences. In contrast, the flows of path 1 and path 3 are utilized more efficiently by the VN-CMT solution as the TSNs increase steeply, while path 2 has not been used at all. This confirms that VN-CMT can find the best path set for data multipath concurrent transfer and distribute data according to each path's capacity, achieving higher data delivery efficiency.

The packets are received out-of-order due to the dissimilar path characteristics and their reordering. This is likely to cause performance degradations. For example, when using CMT, a packet lost in path 2 around 20.2 s is detected and retransmitted at around 20.5 s. The path with the lost trunk fails abruptly for about 0.3 s seconds and resumes later. The subsequent data chunks which arrived in this period are held in the transport layer receive buffer and unable to be delivered to the application. This phenomenon blocks the receiver buffer and seriously decreases the delivery performance. With packet disorder-reducing path group selection and retransmission policy, VN-CMT discards the bad path and retransmits packets in the path with high performance. In this way, VN-CMT greatly reduces disorder
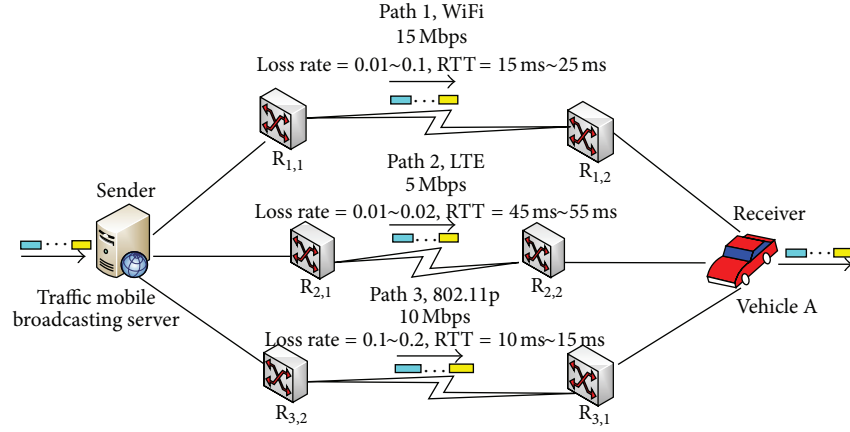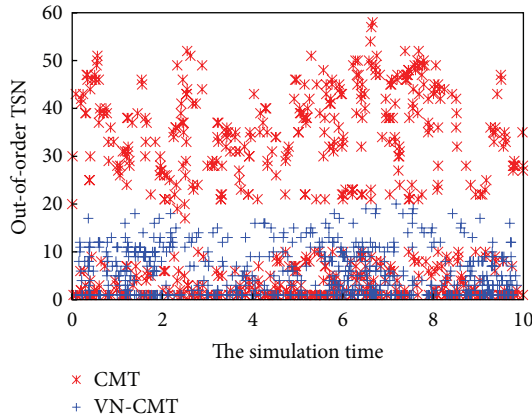
FIGURE 4: Simulation network topology.

FIGURE 5: Comparison of out-of-order TSN.

FIGURE 6: Comparison of packet sending and receiving times in CMT.

and data chunks are received smoothly, as shown in Figure 7. Another important impact factor on performance is spurious retransmission. Spurious retransmission brings additional useless packets and decreases data transfer rate. It is mainly caused by disorder of packets. In order to compare the spurious retransmission between CMT and VM-CMT, we define the rate of spurious retransmission (RSR) to be

$$RSR = \frac{NumR - NumD}{NumD},$$

$$(17)$$

where Num$R$ represents the numbers of packets which are transmitted and Num$D$ represents the numbers of packets which are dropped. In Figure 8, we can see how VN-CMT scheme can highly decrease the rate of spurious retransmissions.

(3) *Average throughput*: Figures 9, 10, and 11 compare average throughput when delivering content with receiver buffer sizes of 32 KB, 64 KB, and 128 KB, respectively. Three groups of simulations were run in order to study the effect of the receiver buffer size on the throughput. It can be seen how the throughput of both schemes increases with the increase in the receiver buffer size. Compared with CMT, VN-CMT tolerates better packet loss and utilizes more efficiently the available aggregate bandwidth from different links. For instance, after 140 s of simulation time with a 32 KB receiver buffer, VN-CMT throughput is 39% higher than that of CMT. With a 64 KB receiver buffer size, VN-CMT throughput is 18% higher than that of CMT. Similarly, VN-CMT performs 10% better than CMT when a 128 KB receiver buffer was employed.
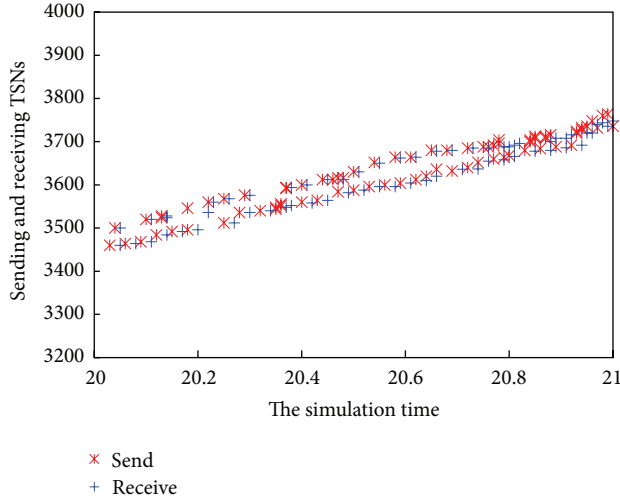
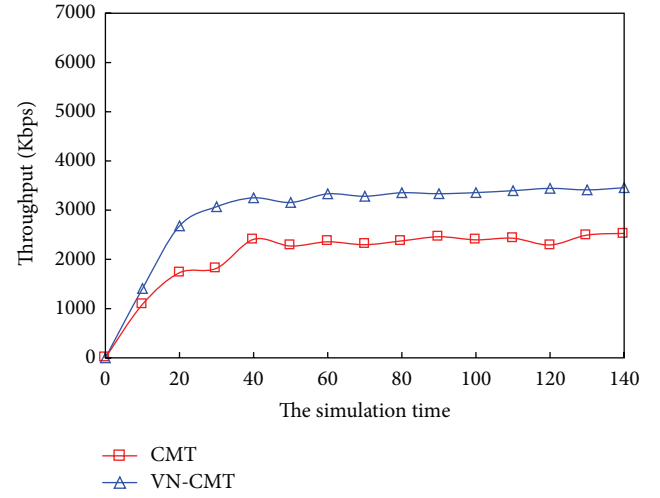FIGURE 7: Comparison of packet sending and receiving times in VN-CMT.

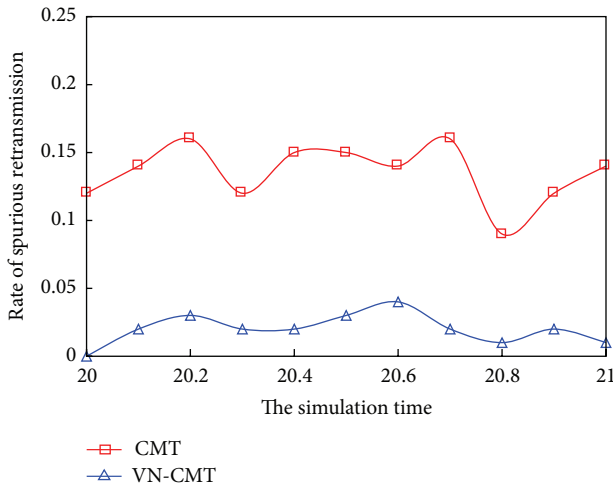FIGURE 9: Comparison of throughput. Rbuf = 32 K.
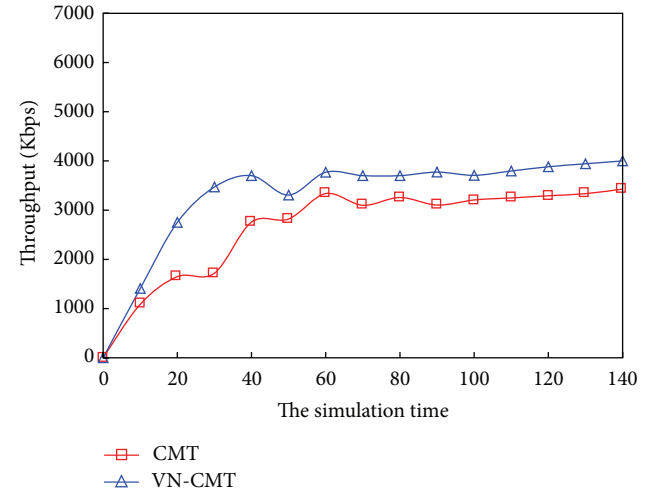

FIGURE 8: Comparison of spurious retransmission.

FIGURE 10: Comparison of throughput. Rbuf = 64 K.

It can be noted how VN-CMT performs better than CMT in all cases. The difference is very much in favour of VN-CMT in limited receiver buffer situations. The packet disorder-reducing path group selection algorithm, retransmission policy, and data scheduling algorithm employed by VN-CMT mitigate the disorder of received packets and enable VN-CMT not to need large receiver buffer to store the out-of-order data chunks. Figures 9–11 fully show how VN-CMT outperforms CMT in terms of the throughput.

5. Conclusion

This paper addresses the packet disorder issue for SCTP concurrent multipath transfer in future heterogeneous vehicular sensor networks. A disorder analytic model is proposed which generates useful disorder degree information for CMT. Based on it, a novel packet disorder reducing retransmission policy, a new path group selection algorithm, and a novel data scheduling algorithm were proposed. The path group selection algorithm aims to find the optimum path set for data concurrent transfer. The data scheduling algorithm analyses every path's quality before considering the average path packet gap in its decision process. The retransmission policy combines both RTT and loss rate factors to find a preferred retransmission path, which ensures that packets are retransmitted quickly and successfully. The simulation results fully show how VN-CMT alleviates out-of-data problem and achieves large and steady throughput in comparison with the classic CMT solution.
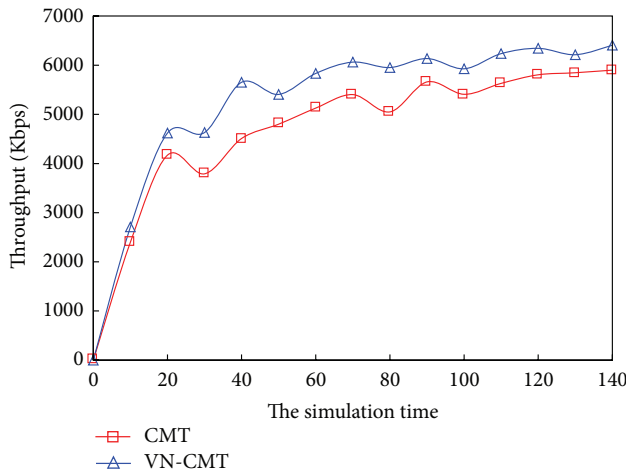
FIGURE 11: Comparison of throughput. Rbuf = 128 K.

Acknowledgments

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