Optimization of the Mobile Router and Traffic Sources in Vehicular Delay Tolerant Network

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Abstract—Vehicular delay tolerant network (VDTN) is introduced for the communications between traffic sources and sinks in which the direct end-to-end connection among them is not available. In this VDTN, mobile routers installed on the vehicles are used as carriers to carry data from traffic sources to sinks. We first present the optimization formulation based on the constrained Markov decision process (CMDP) to obtain an optimal decision of a mobile router whether or not to accept packets from a traffic source. This decision is made to maximize the reward of data delivery while the quality of service (QoS) performance is guaranteed. Then, the noncooperative game and optimization formulations are presented for the decision of the traffic sources to choose optimal packet transmission rate. These noncooperative game and optimization formulations are used for different scenarios, i.e., when the traffic sources have self-interest to maximize their own benefit and global-interest to maximize total benefit of the network, respectively. From the performance evaluation, a mobile router with CMDP optimization can achieve larger reward than that without CMDP while the maximum packet blocking probability requirement is met. With noncooperative game formulation for the traffic sources, the Nash equilibrium can be obtained so that none of the traffic sources can unilaterally deviate. Alternatively, if the traffic sources are cooperative, the largest total benefit of the network can be achieved.

Keywords—Delay tolerant network, vehicular communications, optimization.

I. INTRODUCTION

Delay or disruption tolerant network (DTN) has been introduced for the situation where the connection among nodes in the network is sparse. As a result, unlike traditional mobile ad hoc network (MANET), the end-to-end path between a source and a destination (e.g., gateway or sink) in DTN will only be available for a brief and unpredictable period of time. DTN has attracted research attention due to its variety of applications in military, disaster recovery, and emergency response systems where the communication infrastructure may not exist. In DTN, the data from the source is relayed through mobile nodes to the destination. However, when the connection to other nodes is not available, the data is stored in the buffer of the mobile node. Once the mobile node travels into the transmission range of the mobile node, the data in the buffer can be forwarded to the next hop. In this way, the packet can reach the destination by hopping over the mobile nodes even though the connection between the mobile nodes may not be always available. The major research issues in DTN include the routing protocol [1], [2], [3], the investigation of DTN in various applications [4], [5], [6], [7], [8], and the performance analysis [9], [10], [11], [12], [13], [14], [15]. However, the current literature on DTN research does not consider the optimization of buffer management mechanism nor queuing model for mobile routers. More importantly, the interaction among the traffic sources in the DTN under noncooperative or cooperative environment has never been considered.

In this paper, we consider DTN based on the vehicular communications, which is referred to as vehicular delay tolerant network (VDTN). In VDTN, the traffic sources and sinks do not have a direct transmission path to each other. However, a vehicle with a mobile router is used as a carrier to carry the data from traffic sources to sinks. Each mobile router is equipped with an on-board unit and each source/sink is equipped with a roadside unit. When the vehicle with the mobile router moves into the transmission range of the roadside unit, the traffic source transmits the data packet to the on-board unit of the mobile router. The data is stored in the buffer of the mobile router when the vehicle travels. Once the vehicle moves into the transmission range of the sink, the mobile router transmits data in its queue to the roadside unit of the sink. Note that this packet delivery scheme is similar to the core-aided scheme in [9], in which the packet is stored and forwarded by the core node (i.e., mobile router).

With this VDTN, the decision optimizations of the mobile router and traffic sources are proposed. The mobile router makes decision whether or not to accept the incoming packets from the traffic source based on two criteria. First, as the packets from different traffic sources can have different weights, the mobile router has an objective to maximize the reward defined based on the weights of packets from the traffic sources. Second, the quality of service (QoS) requirements of the traffic sources must be met. In particular, the packet blocking probability of each traffic source needs to be maintained below a threshold. The constrained Markov decision process (CMDP) is formulated and the optimal decision policy for the mobile router is obtained. Furthermore, when the mobile router optimizes its decision based on the optimal policy, the traffic sources make decision in choosing the packet transmission rate which is equivalently the packet arrival rate at the mobile router. Since not all packets will be accepted by the mobile router due to the limited buffer size, a traffic source can maximize its benefit by minimizing the number of blocked packets which is considered to be the cost (e.g., due to the power consumption of packet transmission). Two scenarios of traffic sources in VDTN are considered, i.e., noncooperative and cooperative. These noncooperative and cooperative scenarios correspond to the cases when the traffic sources have self-interest to maximize their own benefit and global-interest
to maximize the total benefit of the network, respectively. In the former, noncooperative game is formulated and the packet transmission rate is obtained from the Nash equilibrium. This equilibrium solution ensures that none of the traffic sources can improve its benefit given that other sources also apply equilibrium solution. In the latter, optimization problem is formulated and the optimal strategy of packet transmission rate is obtained such that the total benefit of all traffic sources is maximized.

The rest of this paper is organized as follows. The related work is reviewed in Section II. Section III describes the system model and assumptions. Optimization formulation based on CMDP for the mobile router is presented in Section IV. Section V considers the competition and cooperation of the traffic sources to transmit packets to the mobile router. Section VI presents the performance evaluation results. The summary of the work is presented in Section VII.

II. RELATED WORK

Routing is one of the important issues in DTN [1], [2], [3]. The major objective of routing in DTN is to deliver packets from the source to the destination by means of mobility of nodes. Since the end-to-end path may not be available, routing schemes have to optimize the data dissemination by utilizing the connectivity information and network conditions maintained by each node. For example, in [1], the routing scheme based on the estimates of the average inter-contact time between the mobile nodes in the network was proposed. This routing scheme was designed to minimize the packet delivery time. The routing properties in terms of loop-free forwarding and polynomial convergence were studied which ensure the performance of the packet delivery in DTN. In [2], the packet delivery scheme based on the super-node architecture and epidemic routing was introduced. With epidemic routing, the packets are forwarded to other contacted nodes (i.e., nodes with a direct connection). Unlike traditional epidemic routing, the packets are forwarded to the super nodes to improve the performance and reduce overhead. The super nodes are then responsible to carry the packets to the destination. Besides the routing protocols discussed above, a survey on the routing protocols in DTNs can be found in [3].

DTN has been applied to many applications (e.g., [4], [5], [6], [7]). In [4], vehicle-to-vehicle (V2V) communications based on DTN were proposed. In [4], the issues of V2V communications in high and predictable mobility, large scale network, and partitioned network were discussed. Also, the experimental platform was developed. In [5], the sensor network based on DTN was applied to monitor lake water quality in rural lake and noise level logging in urban areas and along highways. The prototype for these applications was also developed. In [6], the application of DTN in business application was reported and a coordination protocol was developed. Such a protocol can be used for financial application in a mobile network environment. With DTN architecture, the distributed transaction processing and management can be supported even though the connection among business entities is not always available. In [7], DTN was applied to underwater sensor networks which enable a wide range of aquatic applications including oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. An adaptive routing protocol was proposed for such a DNT based underwater sensor network.

To understand the performance of DTN under node mobility, the analytical models were proposed (e.g., [9], [10], [11], [12], [13], [14]). For examples, in [9], the mobility model for a mobile node in DTN was presented. Given this mobility model, the packet delivery ratio and delay were analyzed. In addition, the queueing model of the traffic source was formulated. In [10], the performance of epidemic routing scheme was studied using continuous-time Markov chain. The state of the system is the number of nodes in the network having the packet. The packet reaching the sink is considered to be the absorbing state in the model. The delay of the packet delivery was derived. In [11], the performances of homing pigeon based DTN were analyzed. In such a network, each node has a dedicated messenger (i.e., pigeon). This messenger periodically carries a batch of packets from the home node (i.e., source node), delivers to the destinations, and returns home. The travel of a messenger has the fixed route and speed. The analytical model was developed to obtain the waiting time of the individual and bulk packets.

However, none of the aforementioned work considered the buffer at a mobile router. The optimization of the buffer management is the key to achieve the best benefit of the DTN while the QoS performance is guaranteed.

III. SYSTEM MODEL AND ASSUMPTIONS

A. Network Model

We consider a network with a set of locations denoted by \( \mathbb{L} \). At each location, there is a stationary node which could be traffic source or sink. The data (i.e., packet) at traffic source \( i \) needs to be delivered to sink \( i' \) for \( i' \neq i \). This network of traffic sources and sinks can be described as the directed graph \( G(\mathbb{L}, \mathcal{E}) \) where \( \mathbb{L} \) is a set of vertices (i.e., the locations of stationary nodes) and \( \mathcal{E} \) is a set of ordered pairs of vertices (i.e., directed edge). The edge \( E(i, i') = 1 \) means that there is traffic demand from traffic source \( i \) to sink \( i' \) where \( i, i' \in \mathbb{L} \). In particular, \( i' \) is the direct successor of \( i \) or \( i \) is the direct predecessor of \( i' \).

In this network, there is no direct connection between any traffic source and sink. Therefore, the packets from traffic source are delivered to sink with the help of mobile routers. The total number of mobile routers in the network is \( N \). Each mobile router may visit different locations randomly at a random speed. An ordered set of locations in which the mobile router \( n (1 \leq n \leq N) \) visits is denoted by \( \mathbb{V}_n \subseteq \mathbb{L} \). When the mobile router visits the location with traffic source \( i \), this traffic source transmits the packet with destination at sink \( i' \) to the mobile router \( n \) if and only if \( E(i, i') = 1 \) and \( i' \in \mathbb{V}_n \). If the packet is accepted by the mobile router, it will be stored in a buffer. Once the mobile router travels and visits the corresponding sink \( i' \), the packet is transmitted by the

\(^{1}\) For brevity, the traffic source at location \( i \in \mathbb{L} \) is called traffic source \( i \) and similarly the sink at location \( i' \in \mathbb{L} \) is called sink \( i' \).
mobile router to the sink. Note that the packet transmissions between traffic source and mobile router and between mobile router and sink are on the time-slot basis. However, there is no strict delay constraint for the packet delivery from traffic source to sink in this network.

B. Vehicular Delay Tolerant Network

To support the packet delivery of above network, VDTN is used. As aforementioned, two major components in this network are roadside unit and on-board unit. While roadside unit is used for the packet transmission of the traffic source and the reception of the sink, on-board unit is used for the packet reception and transmission of the mobile router. In this case, each roadside unit is connected with each traffic source and sink, while on-board unit is connected with the mobile router.

1) Traffic Source: The packet transmitted from the traffic source $i$ to mobile router $n$ to be delivered to sink $i'$ is modeled using batch Markovian arrival process (BMAP) [17]. BMAP is a general model which can capture burstiness of the traffic source. This BMAP is described by the matrices $A(i)_{a-n}$ for $a \in \{0, 1, \ldots, a_m\}$ transmitted packets where $a_m$ is the maximum batch size (i.e., the maximum number of packets transmitted in one time slot). The element of matrix $A(i)_{a-n}$ is denoted by $A(i)_{a-n}(g, g')$ which is the probability of traffic source $i$ changing phase from $g$ to $g'$ and $a$ packets being transmitted to mobile router $n$. The matrix $A(i)_{a-n}$ is defined as $A(i)_{a-n} = [A(i)_{a-n}(g, g')]_{(a_m \times a_m)}$. Let $\Psi_{i-n} = [\psi_{i-n}(1) \cdots \psi_{i-n}(g) \cdots \psi_{i-n}(G_{i-n})]$ denote the steady state probability vector of traffic source $i$. The element $\psi_{i-n}(g)$ of this matrix is the steady state probability that traffic source $i$ will be in phase $g$. This vector can be obtained by solving $\Psi_{i-n} A(i)_{a-n} = \Psi_{i-n}$ and $\Psi_{i-n} 1 = 1$ where 1 is a vector of ones with appropriate size. The average packet transmission rate of traffic source $i$ (i.e., the packet arrival rate of mobile router $n$ with the destination at sink $i'$) can be obtained from

$$\lambda^{(n)}_{i-i'} = \sum_{a=1}^{a_m} \psi_{i-n}(g)(A(i)_{a-n} 1). \quad (1)$$

2) Mobile Router: A mobile router uses separate queues to buffer the packets to be delivered to different sinks. Due to the limited queue size, the transmitted packets from the traffic source can be accepted or refused by the mobile router (the optimal decision of packet acceptance or refusal by the mobile router will be presented later). If the mobile router accepts the packet, it will be stored in a queue. In this case, the packets with destination at sink $i'$ from all traffic sources $i$ for which $E(i, i') = 1$ are aggregated into the same queue.

Since a vehicle can travel among locations in a network, the mobility of the corresponding mobile router $n$ is modeled using transition matrix $M^{(n)}$ which is defined as follows:

$$M^{(n)} = \left[ \begin{array}{cccc} m_{1,1}^{(n)} & \cdots & m_{1,n}^{(n)} \\ \vdots & \ddots & \vdots \\ m_{n,1}^{(n)} & \cdots & m_{n,n}^{(n)} \end{array} \right] \quad (2)$$

where $I_n = \max(\psi_n)$ is the largest index of the location to be visited by mobile router $n$. An element $m_{i,j}^{(n)}$ for $\sum_{j \in \psi_n} m_{i,j}^{(n)} = 1$ denotes the probability of mobile router $n$ staying at location $i$ in the current time slot and moving to location $j$ in the next time slot. In this case, the steady state probability vector $\Omega^{(n)} = [\omega_1^{(n)} \cdots \omega_i^{(n)} \cdots \omega_n^{(n)}]$ whose element $\omega_i^{(n)}$ indicates the probability of mobile router $n$ to be at location $i$ can be obtained by solving $\Omega^{(n)}M^{(n)} = \Omega^{(n)}$ and $\Omega^{(n)} 1 = 1$.

Assuming that the infinite automatic repeat request (ARQ) error control is used, the packet departure (i.e., successful transmission) from mobile router $n$ to sink $i'$ can be modeled as a batch Markovian process. In this case, the packet departure is described by the matrices $D_{n-i'}^{(d)}$ for $d \in \{0, 1, \ldots, d_m\}$ departing packets where $d_m$ is the maximum batch size (i.e., the maximum number of packets transmitted from a mobile router to a sink in one time slot). The element of matrix $D_{n-i'}^{(d)}$ is denoted by $D_{n-i'}^{(d)}(h, h')$ which is the probability that $d$ packets depart mobile router $n$ to sink $i'$ and the phase changes from $h$ to $h'$. Again, the matrix $D_{n-i'}^{(d)}$ is defined as $D_{n-i'}^{(d)} = D_{n-i'}^{(d_0)} + \cdots + D_{n-i'}^{(d_i)} + \cdots + D_{n-i'}^{(d_{d_m})}$. Let $\Gamma_{n-i'} = [\gamma_n, \gamma_{n-i'}(h), \gamma_{n-i'}(H_{n-i'})]$ denote the steady state probability vector of mobile router $n$. This element of this matrix $\gamma_{n-i'}(h)$ is the steady state probability that the departure phase of mobile router $n$ is $h$. This vector can be obtained by solving $\Gamma_{n-i'} D_{n-i'} = \Gamma_{n-i'}$ and $\Gamma_{n-i'} 1 = 1$. The average packet departure rate from mobile router $n$ to sink $i'$ can be obtained from

$$\mu_{n-i'} = \sum_{d=1}^{d_m} d \Gamma_{n-i'}(D_{n-i'}^{(d)} 1). \quad (3)$$

Note that finite state Markov chain (FSMC) wireless channel model [16] is a special case of this batch Markovian process.

In this VDTN, we assume that there is no direct packet exchange among mobile routers. Firstly, the DTN is typically established over a large and sparse area (e.g., in the rural area). Also, the number of mobile routers is generally small. Therefore, the chance that the mobile routers will be in the vicinity of each other and be able to communicate is small, making packet exchange little beneficial. Secondly, the packet exchange among mobile routers results in much more complicated buffer management mechanism. Also, the on-board unit of the vehicle will be more complex to handle the communications among mobile routers in a short period of time, especially in the high speed vehicles. Thirdly, the packet exchange among mobile routers incurs much more amount of duplicated packets to be stored in the buffer. As a result, the size of free buffer (i.e., space in queue) which will be used to store the new packets from the traffic sources is smaller, and the QoS performance (e.g., packet blocking probability) will be degraded.

IV. OPTIMIZATION FORMULATION FOR MOBILE ROUTER

In this section, the constrained Markov decision process (CMDP) is formulated to obtain an optimal decision of a mobile router whether or not to accept the packets from a traffic source to be delivered to a sink. Specifically, the
decision is to allow or refuse the packet to enter a particular queue. Note that since the decision for each queue which corresponds to different sinks is made independently, the same formulation can be applied for all queues in all mobile routers. For the following formulation, the state space, action space, and probability transition matrix are defined. Then, the method to obtain the optimal policy of this CMDP formulation is presented. With the steady state probability of the queue, the performance measures of the mobile router are derived.

A. State Space and Action Space

The composite state of the CMDP formulation for a queue at mobile router \( n \) buffering packets with destination at sink \( i' \) is defined as follows

\[
\Delta = \{ (V, X, A, D); V \in \mathbb{V}_n, X \in \{0, 1, \ldots, X\}, A \in \mathcal{A}, D \in \{1, \ldots, H_{n-i'}\} \}
\]

(4)

where \( V \) is the location of mobile router \( n \), \( X \) is the number of packets in queue, \( A \) is the composite phase of packet arrival, and \( D \) is the phase of packet departure. \( X \) is the maximum queue size, and the set \( \mathcal{A} \) is defined as

\[
\mathcal{A} = \bigcup_{i \in \mathbb{S}_n} \{ A_i \}
\]

(5)

for \( A_i \in \{1, \ldots, G_{t-n} \} \) where \( \mathbb{S}_n \subseteq \mathbb{V}_n \) is a set of locations with traffic sources (i.e., a set of traffic sources) visited by the mobile router \( n \), and \( G_{t-n} \) is the number of packet transmission phases of traffic source \( i \).

The action space is defined as \( \mathbb{U} = \{0, 1\} \). The actions \( u = 0 \) and \( u = 1 \) correspond respectively to accepting and refusing the incoming packet by the mobile router. Here, the decision of refusing the incoming packet from some traffic sources at the mobile router may be required to avoid congestion so that the QoS requirements of all traffic sources can be met.

B. Probability Transition Matrix

The probability transition matrix of the state defined in space \( \Delta \) can be derived based on the action, i.e., \( P(u) \) for \( u \in \mathbb{U} \).

1) Accepting Incoming Packet (\( u = 0 \)): In this case, all incoming packets are accepted and stored in a queue of the mobile router. At the first step, we consider the packet arrival process of the queue. In this case, the packet from traffic source \( i \) can arrive at the queue only when the mobile router is at the corresponding location (i.e., \( V \in \mathbb{S}_n \)). Otherwise, there is neither packet arrival from other traffic source nor packet departure to sink \( i' \) for \( i' \neq i \). Therefore, the probability transition matrix for a packet arrivals from traffic source \( i \) with phase transition of all other sources \( j \neq i \) can be expressed as follows:

\[
B_i^{(a)}(u) = \left( \bigotimes_{j \in \mathbb{S}_n, j < i} A_{j-n} \right) \otimes \left( \bigotimes_{j \in \mathbb{S}_n, j > i} A_{j-n} \right)
\]

for \( a \in \{0, 1, \ldots, A_m\} \) and \( i \in \mathbb{S}_n \), where \( \otimes \) is the Kronecker product. This matrix \( B_i^{(a)}(u) \) captures the transition of \( A \) defined in (4).

At the second step, the packet departure process of the queue of mobile router \( n \) for the packet with destination at sink \( i' \) is considered. If a mobile router is at location \( i \), the packet in this queue cannot depart. Although the mobile router could carry the packets with the destination at the sink \( i \), these packets will be stored in the different queue. The probability transition matrix becomes \( C_i^{(a)} = B_i^{(a)}(u) \otimes D_{n-i'} \) where \( D_{n-i'} \) represents the phase transition of packet departure of mobile router \( n \). In contrast, if a mobile router is at sink \( i' \), i.e., \( V \neq i' \), the packets in queue may depart. Similarly, the probability transition matrix for \( d \) departing packets from mobile router \( n \) combining phase transition of all traffic sources \( i \neq i' \) can be expressed as follows:

\[
E_i^{(d)} = \bigotimes_{d \in S_n} A_{i-n} \otimes D_{n-i'}
\]

for \( d \in \{0, 1, \ldots, d_m\} \). However, if \( i \notin \mathbb{S}_n \) and \( i \neq i' \) (i.e., a mobile router is at the location without both traffic source and sink), the probability transition matrix becomes \( F_i = \bigotimes_{d \in S_n} A_{i-n} \otimes D_{n-i} \). In particular, there is no packet arrival and departure at the location \( i \in \mathbb{S}_n \). Note that the matrices \( C_i^{(a)} \), \( E_i^{(d)} \), and \( F_i \) capture the transitions of \( (A, D) \) defined in (4).

At the third step, the location transition of mobile router \( n \) is combined. The probability transition matrix \( N^{(k)} \) has the element \( N_{i,j}^{(k)} \) for \( i \in \{1, \ldots, I_n\} \) and \( k = \{d_m - d_m + 1, \ldots, 0, \ldots, a_m - 1, a_m\} \) where \( I_n = \max(V_n) \). Note that the matrix \( N^{(k)} \) captures the location transition of \( (V, A, D) \) defined in (4). The element \( N_{i,j}^{(k)} \) is the probability transition matrix of mobile router \( n \) from location \( i \) to \( j \) for \( i, j \in \mathbb{V}_n \) when the number of packets in queue increases by \( k \) for \( k > 0 \), decreases by \(|k|\) for \( k < 0 \), or does not change for \( k = 0 \). This element can be obtained from

\[
N_{i,j}^{(k)} = \begin{cases} m_{i,j}^{(n)} C_i^{(k)}, & k \geq 0 \\ m_{i,j}^{(n)} D_{i}^{(k)}, & k < 0 \end{cases}
\]

(6)

for \( i \in \mathbb{S}_n \) and \( j \in \mathbb{V}_n \) where \( 0 \) is the matrix of zeros. Again, for \( i \in \mathbb{S}_n \cap \{i'\} \), the element \( N_{i,j}^{(k)} \) becomes

\[
N_{i,j}^{(k)} = \begin{cases} m_{i,j}^{(n)} F_i, & k = 0 \\ 0, & \text{otherwise}. \end{cases}
\]

(7)

Note that the matrix \( N_{i,j}^{(k)} \) defined in (6) and (7) is the combination of the state transition for the location of mobile router (i.e., from location \( i \) to location \( j \)) and the packet arrival and departure processes.

At the fourth step, the transition of the number of packets in queue with size \( X \) is combined. The probability transition matrix for \( u = 0 \) is denoted by \( P(u) \) whose element is denoted by \( P_{x,y} \). The element \( P_{x,y} \) is the probability transition matrix for the number of packets in queue changing from \( x \in \{0, 1, \ldots, X\} \) to \( y \in \{x - d_m, \ldots, x + a_m\} \). This element can be simply obtained from \( P_{x,y} = N^{(x-y)} \). Note that the matrix \( P(u) \) captures all transitions of state \( s \in \Delta \) defined in (4).

2) Refusing Incoming Packet (\( u = 1 \)): In this case, all incoming packets are refused by a mobile router. The derivation of the probability transition matrix \( P(u = 1) \) is similar to the case of \( u = 0 \). The difference is at the first step in which the
number of packets in queue cannot increase when a mobile router is at the traffic sources \( i \) for \( i \neq i' \). In this case, the probability transition matrix for a packet arrival from traffic source \( i \) becomes

\[
B_i^{(a)}(u = 1) = \begin{cases} 
\bigotimes_{j \in S_n} A_{j \rightarrow n}, & a = 0 \\
0, & 0 < a \leq a_m. 
\end{cases}
\]  

(8)

The second, third, and fourth steps are same as those of \( u = 0 \). In this case, the element of matrix \( P(u = 1) \) becomes \( P_{x,0} = 0 \) for \( y > x \), since the number of packets in queue cannot increase.

C. Objective and Constraints

In VDTN, the packets from different traffic sources may have different weights depending on the values of the information included in the packets. Therefore, in a long term, a mobile router has to make a decision such that the reward defined as the sum of the weights of delivered packets is maximized. However, since the resource of a mobile router is limited (i.e., queue size is finite), again in a long term, QoS requirements (i.e., the maximum packet blocking probability) of all the traffic sources have to be satisfied. These long-term reward \( J_R \) and packet blocking probability \( J_{B,i} \) can be defined as follows \( J_R = \lim_{t \rightarrow \infty} \frac{1}{t} \sum_{t'=1}^{t} E(\mathcal{R}(S_{t'}, U_{t'})) \) and \( J_{B,i} = \lim_{t \rightarrow \infty} \frac{1}{t} \sum_{t'=1}^{t} E(\mathcal{B}_i(S_{t'}, U_{t'})) \) where \( S_t \in \Delta \) and \( U_t \in \mathcal{U} \) are the state of a queue and action of a mobile router at time \( t' \), respectively. \( \mathcal{R}(s, u) \) and \( \mathcal{B}_i(s, u) \) for \( s \in \Delta \) and \( u \in \mathcal{U} \) are the immediate and immediate packet blocking probability functions, respectively. These functions have the parameters of composite state \( s \) and action \( u \). Note that the composite state \( s \) is defined as \( s = (s_1, s_2, s_3, s_4) \). The element of this composite state \( s \) is the realization of the variables defined in (4), i.e., the visiting location of a mobile router \( s_1 \), the number of packets in queue \( s_2 \), the phase of packet transmission of all traffic sources \( s_3 \), and the phase of packet departure \( s_4 \). Again, \( s_i \) is a composite state which is defined as \( s_i = (\ldots, s_{a,i}, \ldots) \) for \( i = \mathbb{S}_n \) where \( s_{a,i} \) is the phase of packet transmission of traffic source \( i \).

1) Immediate Reward: Let \( w_{i \rightarrow i'} \) denote the weight of a packet from source \( i \) to be delivered to sink \( i' \). The immediate reward of mobile router \( n \) is a function of the number of accepted packets. Therefore, the immediate reward function can be defined as in (9). If the number of incoming packets \( a \) is larger than the available space in queue \( X - s_x \), the maximum number of accepted packets will equal to the available space \( X - x_s \). Note that once the packet is accepted by a mobile router, it will be stored in queue and delivered to the sink \( i' \) eventually. Therefore, no packet will be lost due to channel error.

2) Immediate Packet Blocking Probability: The packets can be blocked either due to the lack of available space in queue or due to the action of a mobile router (i.e., \( u = 1 \)). The immediate packet blocking probability (i.e., the ratio of the number of blocked packets to the total transmitted packets upon each action of the mobile router) when a mobile router visits traffic source \( i \) can be defined as in (10).

D. Optimal Policy

The reward and QoS performance of the traffic sources depend not only on the state but also on the decision of a mobile router. This decision can be obtained from the optimal policy of the constrained Markov decision process (CMDP). The policy is defined as \( u = \pi(s) \) which is a mapping of the state \( s \) to the action \( u \). The policy of CMDP can be deterministic or randomized. For the randomized policy, the probability distribution denoted by \( \nu(\pi(s)); s \in \Delta, \pi(s) \in \mathcal{U} \) for \( \sum_{s \in \mathcal{U}} \nu(\pi(s)) = 1 \). In other word, \( \nu(u) \) for \( u = \pi(s) \) is the probability of a mobile router to take action \( u \) at state \( s \). An optimal policy \( \pi^* \) is defined as the policy that the long-term objective is maximized while all long-term constraints are met. For the mobile router, the objective is defined as the reward of packet delivery from traffic sources to sink. The constraint is to maintain the packet blocking probability of traffic sources \( i \) below the threshold \( B_{\text{max},i} \). The optimization problem can be formulated as follows:

Maximize: \( \mathcal{J}_R(\pi) \) \hspace{1cm} (11)

Subject to: \( \mathcal{J}_{B,i}(\pi) \leq B_{\text{max},i} \) \hspace{1cm} (12)

for \( i \in \mathbb{S}_n \). In this case, the reward and packet blocking probability are defined as the functions of policy \( \pi \).

To obtain the optimal policy \( \pi^* \), the CMDP formulation defined in (11)-(12) can be transformed into an equivalent linear programming (LP) problem [18]. In particular, there is a one-to-end mapping between the optimal solution \( \phi^*(\cdot) \) of the LP problem and the optimal policy \( \pi^* \) of CMDP formulations. Also, the LP solution is feasible if and only if CMDP formulation is feasible. Let \( \phi(s, u) \) denote the steady state probability that action \( u \) is chosen when the state is \( s \). The optimization problem (i.e., LP) corresponding to the CMDP formulation defined in (11)-(12) can be expressed as follows:

Maximize: \( \sum_{s \in \Delta} \sum_{u \in \mathcal{U}} \mathcal{R}(s, u)\phi(s, u) \) \hspace{1cm} (13)

Subject to: \( \sum_{s \in \Delta} \mathcal{B}_i(s, u)\phi(s, u) \leq B_{\text{max},i}, \) \hspace{1cm} (14)

\( \sum_{u \in \mathcal{U}} \phi(s', u) = \sum_{s \in \Delta} \sum_{u \in \mathcal{U}} P(s'|u)\phi(s, u) \) \hspace{1cm} (15)

\( \sum_{s \in \Delta} \sum_{u \in \mathcal{U}} \phi(s, u) = 1, \ \phi(s, u) \geq 0 \) \hspace{1cm} (16)

where \( P(s'|u) \) is the probability that the state changes from \( s \) to \( s' \) when action \( u \) is chosen. This probability is the element of matrix \( P(u) \). The objective and constraint in (13) and (14) correspond to those in (11) and (12), respectively. The constraint in (15) satisfies the Chapman-Kolmorogov equation of the Markov process. Let \( \phi^*(s, u) \) denote the optimal solution of LP problem defined in (13)-(16). The optimal policy \( \pi^* \) for CMDP formulation is the randomized policy which can be uniquely mapped from the optimal solution of LP problem as follows:

\( \nu(u) = \pi^*(s) = \frac{\phi^*(s, u)}{\sum_{u' \in \mathcal{U}} \phi^*(s, u')} \) \hspace{1cm} (17)

for \( \sum_{u' \in \mathcal{U}} \phi^*(s, u') > 0 \). Otherwise, the specific action \( u = 0 \) is chosen. The optimal solution \( \phi^*(s, u) \) can be obtained using a standard method for solving LP.
\[
\mathcal{R}(s, u) = \begin{cases} 
\sum_{n=1}^{m} \omega_{n} \left( \sum_{g=1}^{A_{1:n}} A_{1:n}^{(n)}(s_{n}, g) \right), & s_{n} \leq X - a_{m}, s_{v} = i, u = 0 \\
\sum_{n=1}^{m} \left( X - s_{x} \right) \left( \sum_{g=1}^{A_{1:n}} A_{1:n}^{(n)}(s_{n}, g) \right), & s_{x} > X - a_{m}, s_{v} = i, u = 0 \\
0, & \text{otherwise.}
\end{cases}
\]

\[
\mathcal{R}_{i}(s, u) = \begin{cases} 
\sum_{a=1}^{a} \left( \sum_{g=1}^{A_{1:a}} A_{1:a}^{(a)}(s_{a}, g) \right), & s_{n} > X - a_{m}, s_{v} = i, u = 0 \\
1, & \text{otherwise.}
\end{cases}
\]

\[\pi \text{ steady state probability when an optimal policy } \pi^{*}(s) \text{ is applied.}\]

\[\pi^{*} \text{ is the probability transition matrix when the optimal randomized policy } \pi^{*}(s) \text{ is applied.}\]

\[E. \text{ Performance Measures}\]

To obtain the performance measures of the queue, the steady state probability when an optimal policy } \pi^{*}(s) \text{ is applied would be required. The steady state probability to be in state } s \text{ is denoted by } p_{\pi^{*}}(s) \text{ for } s \in \Delta. \text{ This steady state probability can be obtained by solving the following set of equations } p_{\pi^{*}} P(\pi^{*}) = P_{\pi^{*}} \text{ and } p_{\pi^{*}} 1 = 1, \text{ where } p_{\pi^{*}} = \left[ \ldots p_{\pi^{*}}(s_{e}, s_{x}, s_{a}, s_{d}) \ldots \right]. \text{ } P(\pi^{*}) \text{ is the probability transition matrix when the optimal randomized policy } \pi^{*}(s) \text{ is applied.}\]

\[1) \text{ Average Number of Packets in Queue of a Mobile Router: The average number of packets in queue of mobile router } n \text{ with destination at sink } i' \text{ can be obtained from } \]

\[\begin{aligned}
\tau_{i'}^{(n)}(s, u) &= \sum_{s_{e}=1}^{X} s_{x} 
\sum_{s_{u} \in \Delta} \sum_{s_{a} \in A} \sum_{s_{d}=1}^{H_{n, i'-v}} p_{\pi^{*}}((s_{v}, s_{x}, s_{a}, s_{d})).
\end{aligned}\]

\[2) \text{ Packet Blocking Rate and Packet Blocking Probability: The packet blocking probability (i.e., the ratio of the number of blocked packets to the total transmitted packets in a long term) is obtained from } \]

\[B_{p_{n, i'-v}}(s, u) = \sum_{s_{e} \in \Delta} \sum_{a \in U} p_{\pi^{*}}((s_{v}, s_{x}, s_{a}, s_{d})).\]

\[\text{Note that this packet blocking probability are obtained from the fact that the phase transitions of the packet transmission of all traffic sources are independent.}\]

\[3) \text{ Throughput: The throughput of traffic source } i \text{ transmitting packet to mobile router } n \text{ to the destination at sink } i' \text{ can be obtained from } \]

\[\tau_{i'-v}^{(n)} = \lambda_{i'-v}(n) - B_{i'-v}.\]

\[\text{The total queue throughput from all traffic sources is } \tau_{i'}^{(n)} = \sum_{s_{e} \in \Delta} \tau_{i'-v}^{(n)}.\]

\[\text{The average queuing delay of the mobile router } n \text{ for sink } i' \text{ can be obtained based on Little’s law as follows: } \]

\[\tau_{i'}^{(n)} \text{ is the average number of packets in queue of a mobile router.}\]

The delivery ratio of mobile router } n \text{ for the traffic source } i \text{ to sink } i' \text{ can be obtained from } \]

\[\sigma_{i'-v}^{(n)}(s, u) = \frac{\tau_{i'-v}^{(n)}}{\lambda_{i'-v}^{(n)}}.\]

\[\text{V. \textit{COMPETITION AND COOPERATION AMONG TRAFFIC SOURCES}}\]

In this section, we consider the competition and cooperation among traffic sources transfer their data to the sink through the mobile routers. First, the net reward of the traffic source is defined based on the successful packet delivery to the sink and the cost of packet transmission. Then, the noncooperative game is formulated for competitive traffic sources with self-interests. Alternatively, the cooperation among traffic sources can be established to achieve the highest total net reward. The optimal strategy of the traffic sources is obtained from the optimization formulation.

\[A. \text{ Net Reward}\]

We assume that traffic source } i \text{ can choose packet transmission rate } \lambda_{i}(n), \text{ defined in (1). The net reward of a traffic source is a function of reward due to packet delivered by all mobile routers to all corresponding sinks and the cost of packet transmission to each mobile router. The net reward of traffic source } i \text{ is defined as follows: } \]

\[A_{i}(\lambda_{i}, \lambda_{-i}) = \sum_{n=1}^{N} \sum_{i' \in D_{i}} \left( w_{i'-v} \tau_{i'-v}^{(n)}(\lambda_{i}, \lambda_{-i}) - c_{i} \lambda_{i}(n) \right) \]

\[\text{where } D_{i} \text{ is a set of sinks corresponding to source } i, \text{ i.e., } D_{i} = \{i' \}; E(i, i') = 1, i' \in D_{i}, \text{ and } N \text{ is the total number of mobile routers in the network. } \lambda_{i} \text{ and } \lambda_{-i} \text{ are respectively the vector of packet transmission rates of traffic source } i \text{ transmitted through all mobile routers to all corresponding sinks, and the vector of packet transmission rates of all traffic sources except source } i \text{. } w_{i'-v} \text{ and } c_{i} \text{ are the weight of packet delivered to the sink } i' \text{ and the cost of packet transmission by traffic source } i, \text{ respectively. } \tau_{i'-v}^{(n)}(\lambda_{i}, \lambda_{-i}) \text{ is the throughput of packet delivery (i.e., as in (20)). This throughput is defined as a function of a vector of all packet transmission rates, i.e., } \lambda_{i} = [\lambda_{i}^{(1)} \lambda_{i}^{(2)} \ldots \lambda_{i}^{(N)}].\]

\[I = \left[ \bigcup_{n=1}^{N} S_{n} \right] \text{ is the total number of traffic sources in the network.}\]
B. Competition among Traffic Sources

The noncooperative game formulation of this network can be described as follows. The players of this game are the traffic sources. The strategy of each player is a set of the packet transmission rates. The payoff is the net reward. If all traffic sources are rational to maximize their payoffs, the Nash equilibrium is considered as the solution. The Nash equilibrium of a noncooperative game is a set of strategies \( \lambda_i^* \) with the property that no player can increase his payoff by choosing a different strategy, given other players’ sets of strategies \( \lambda_{-i}^* \). That is,

\[
\mathcal{N}_i(\lambda_i^*, \lambda_{-i}^*) \geq \mathcal{N}_i(\lambda_i, \lambda_{-i}), \quad \forall i. \tag{25}
\]

The Nash equilibrium can be obtained from best response of each player [19]. This best response is defined as an optimal set of strategies of a particular player given the strategies of other players. The best response of traffic source \( i \) is defined as follows:

\[
\lambda_i^* = \mathcal{BR}_i(\lambda_{-i}) = \arg \max_{\lambda_i} \mathcal{N}_i(\lambda_i, \lambda_{-i}) \tag{26}
\]

where \( \arg \max \) is an argument maximization which returns the optimal argument of function \( \mathcal{N}_i(\cdot) \). However, since the net reward which is a function of the throughput, i.e., \( \tau_i(\cdot, \cdot) \), is obtained based on the CMDP optimization, the numerical method is applied to obtain the best response of each traffic source. The Nash equilibrium is considered to be the solution of the following optimization formulation

Minimize: \[
\sum_{i \in \bigcup_{n=1}^N S_n} \left| \lambda_i - \mathcal{BR}_i(\lambda_{-i}) \right|. \tag{27}
\]

C. Cooperation among Traffic Sources

Alternatively, all the traffic sources can cooperate to achieve the highest total net reward which is defined as follows:

\[
\mathcal{F}(\lambda) = \sum_{i \in \bigcup_{n=1}^N S_n} \mathcal{N}_i(\lambda_i, \lambda_{-i}). \tag{28}
\]

An optimization problem can be formulated to obtain the optimal strategy as follows:

\[
\lambda^* = \arg \max_{\lambda} \mathcal{F}(\lambda). \tag{29}
\]

Again, the numerical optimization method is applied to obtain this optimal strategy.

VI. PERFORMANCE EVALUATION

A. Parameter Setting

We consider VDTN as shown in Fig. 1. There are totally 5 locations in which the traffic sources are at locations \( i = S_n = \{1, 2, 3\} \). The sink is at location \( i' = 5 \), while location 4 is the road which has no traffic source or sink. The average distance among traffic sources and sink is 10 km. Note that this setting is typical for the environment monitoring application using VDTN. The traffic sources and sink correspond to the sensors and monitoring center, respectively. The edges of the directed graph representing this network are \( E(1, 5) = E(2, 5) = E(3, 5) = 1 \), and \( E(4, 5) = 0 \). There is a single mobile router in this network (i.e., \( N = 1 \)). The set of locations to be visited by this mobile router is denoted by \( V_1 = \{1, 2, 3, 4, 5\} \).

The vehicle speed is 45km/h. At one time slot, one packet is transmitted from the mobile router to the sink with successful probability denoted by \( \mu = 0.95 \), i.e., \( D_{n \rightarrow i'}(1, 1) = 1 - \mu \) and \( D_{n \rightarrow i'}(1, 1) = \mu \). At the traffic sources, packets are transmitted following truncated Poisson process in which the maximum number of transmitted packets per time slot is \( a_m = 30 \). Note that although this Poisson process is used as an example in the numerical results, the proposed CMDP formulation is general for any process. With Poisson process, the number of phases of each traffic source is one. Given the packet transmission rate \( \lambda_i \) of traffic source \( i \) to be delivered to sink \( i' \), the probability of \( a \) packets arriving at mobile router \( n \) can be obtained from \( A_{s \rightarrow n}^{(a)}(1, 1) = e^{-\lambda_i T} \left( \frac{\lambda_i T^n}{n!} \right) \) for \( a \in \{0, 1, \ldots, a_m - 1\} \) and \( A_{s \rightarrow n}^{(a_m)}(1, 1) = \sum_{n=0}^{\infty} e^{-\lambda_i T} \left( \frac{\lambda_i T^n}{n!} \right) \).

The queue size of mobile router is \( X = 70 \) packets. The weights of the packets from traffic sources 1, 2, and 3 are \( w_1 = 1.0, w_2 = 1.2, \) and \( w_3 = 1.4 \), respectively. The costs of packet transmission from these sources are \( c_1 = 0.975, c_2 = 1.175, \) and \( c_3 = 1.375 \). The maximum packet blocking probability is \( B_{\text{max}, i} = 0.05 \) for \( i = \{1, 2, 3\} \).

B. Numerical Results

1) Performance of Mobile Router: Fig. 2 shows the throughput of three traffic sources for the cases that the mobile router has and does not have CMDP optimization. Without CMDP optimization, all incoming packets are accepted by the mobile router as long as there is the available space in queue. As the packet transmission rates of the sources increase, the throughput increases. However, we observe that at the large packet transmission rate (i.e., \( \lambda_i > 1.5 \) packets/time slot), the throughput of source 3 with CMDP optimization is slightly higher than that without CMDP. In contrast, the throughput of source 1 with CMDP optimization is slightly lower than that without CMDP. Since the packet from source 3 has the largest weight, the mobile router with CMDP yields the priority to this source by accepting more packets. Therefore, the throughput is higher.

Fig. 3 shows the packet blocking probability of the three traffic sources. Again, the blocking probabilities increase as the packet transmission rates increase. In this case, the blocking probability of source 3 is largest while that of source 1 is smallest, since the mobile router has the highest probability of visiting location of source 3 and the lowest probability of visiting location of source 1. When CMDP optimization is applied
to the mobile router, we observe that the blocking probabilities of all traffic sources are bounded at the given maximum threshold (i.e., \( B_{max,i} = 0.05 \forall i \)). However, without CMDP optimization, the blocking probability of source 3 increases constantly and exceeds the threshold. We observe that when the blocking probability of source 3 reaches the maximum threshold (e.g., at \( \lambda_3 > 1.4 \)), the blocking probabilities of other sources (especially source 1) increase rapidly and also reach the threshold. Since the packet from source 3 has the largest weight, the mobile router blocks the packets from sources 1 and 2 whose packets have lower weights. Note that the maximum packet transmission rates of the traffic sources can be determined when the blocking probabilities of all traffic sources reach the threshold.

Fig. 2. Throughput of traffic sources under different packet transmission rates.

Fig. 3. Packet blocking probability under different packet transmission rates with the packet blocking probability constraint.

Fig. 4 shows the difference between the rewards of the mobile router with and without CMDP optimization. Note that the positive value of y-axis indicates that the reward of the mobile router with CMDP optimization is higher than that without CMDP, and vice versa. We observe that at the small packet transmission rate (i.e., \( \lambda_i < 0.7 \)), the rewards of the mobile router with and without CMDP are identical. In the case of small packet transmission rate, most of the packets can be accepted by the mobile router (i.e., the packet blocking probability is small). However, at the large packet transmission rate, the mobile router will block some packets, mostly from the sources which have small weight. As a result, reward of the mobile router with CMDP optimization is higher due to the selective packet acceptance. In contrast, if the packet transmission rate approaches the threshold (i.e., \( \lambda_i = 1.63 \)), the reward of the mobile router without CMDP becomes higher since the mobile router accepts all arriving packets. However, this higher reward without CMDP is at the cost of packet blocking probability constraint violation (Fig. 3) which is undesirable.

2) Maximum Packet Transmission Rate of Traffic Source:

Then, we evaluate the capacity of the traffic source, i.e., the maximum packet transmission rate such that the packet blocking probability requirement is met. Given the packet transmission rates of source 2 and source 3, the maximum packet transmission rate of source 1, i.e., \( \lambda_1 \), is shown in Fig. 5. As expected, the maximum packet transmission rate of one source depends on the packet transmission rates of other sources, since they share the resource of the same mobile router. As the packet transmission rates of source 2 and source 3 increase, the maximum packet transmission rate of source 1 decreases.

Fig. 5. The maximum packet transmission rate of traffic source 1.

Fig. 6 shows the the maximum packet transmission rates of the three sources, with different probabilities that the mobile router stays at the location of the sink (i.e., location 5). As the probability of mobile router to be at the sink increases, the packet transmission rates of all traffic sources increase. In this case, the mobile router has more chances to be at the traffic sources than at the sink, the bottleneck of data transfer is from mobile router to the sink. Therefore, when the mobile router has more chances to transmit packets stored in its queue to the sink, the number of packets remained in queue is smaller.
As a result, the mobile router can accept more packets from the sources, and thus the throughput is higher. Again, since the packet from source 3 has the largest weight, a decision of the mobile router is optimized to accept more packets from this source. Consequently, the maximum packet transmission rate of source 3 is the highest.

Fig. 6. The maximum packet transmission rate under different probabilities of the mobile router staying at the sink.

3) Competition and Cooperation among Traffic Sources:
We consider the competition and cooperation among traffic sources to transmit their packets to the sink (i.e., single hop) given that CMDP optimization is applied to the mobile router. Each source is considered to be a player whose strategy is the packet transmission rate. The payoffs (i.e., net rewards) of these players (i.e., three sources) are shown in Fig. 7. As the packet transmission rate increases, the net rewards first increase. However, at a certain point, the net rewards decrease due to the higher packet blocking probability which results in larger cost to the source. The packet transmission rate of each source that yields the highest net reward is defined as the best response given the packet transmission rates of other sources.

Fig. 7. Net reward of the traffic sources under different packet transmission rates.

Next, to simplify the presentation of the results, we assume that traffic source 3 fixes its packet transmission rate to $\lambda_3 = 1.0$. Only source 1 and source 2 vary their packet transmission rates. The best responses of sources 1 and 2 are shown in Fig. 8. We observe that as one source increases its packet transmission rate, the highest net reward of another source can be achieved if its packet transmission rate decreases. Since the queue of the mobile router becomes congested more easily when one source increases its packet transmission rate, another source has to reduce its packet transmission rate to avoid high cost due to the blocked packets. As a result, the best response of each source decreases as the given packet transmission rate of another source increases. If all sources are noncooperative, the point at which the best responses of all sources intersect is the Nash equilibrium. At this Nash equilibrium, none of the sources can unilaterally deviate to choose different packet transmission rate to improve its net reward.

Fig. 8. Best responses, Nash equilibrium, and optimal transmission rates of traffic source 1 and source 2.

If all traffic sources are cooperative, the total net reward is shown in Fig. 9. As expected, as both sources increase their packet transmission rates, the total net reward first increases and then decreases at the certain point due to the congestion. The point which yields the maximum total net reward is the optimal strategy of both sources. We observe that this optimal strategy is different from the Nash equilibrium, as shown in Figs. 8 and 9. This result indicates that the Nash equilibrium of the packet transmission rates cannot maximize the total net reward. However, although the optimal strategy can achieve the highest total net reward of the network, some sources can deviate to gain higher individual net reward. The method to enforce all sources to cooperate to avoid total net reward degradation may be considered in the future.

Fig. 9. Total net reward of traffic source 1 and source 2, and the locations of Nash equilibrium and optimal strategy.
VII. CONCLUSION

The vehicular delay tolerant network (VDTN) has been considered in this paper. Without direct connection between the traffic sources and the sink, the data can be delivered by a mobile router installed on a vehicle. The on-board unit of the vehicle communicates with the roadside unit of the traffic source and the sink. In this VDTN, the mobile router has to make decision whether to accept or refuse the incoming packet from the traffic source so that the reward from packet delivery is maximized while the QoS (i.e., packet blocking probability) requirement is met. The constrained Markov decision process (CMDP) optimization has been formulated and the optimal policy for the decision of the mobile router is obtained. Furthermore, the traffic source has to make decision on the packet transmission rate so that its benefit is maximized. Non-cooperative and cooperative cases of the traffic sources have been considered. The noncooperative game and optimization problem have been formulated for the former and the latter, respectively. The solutions are obtained in terms of the Nash equilibrium and optimal strategy.

For future work, the communication among mobile router can be considered. The experiment of the VDTN in the actual environment will be also considered.

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