Vehicle-Assisted Data Delivery for Smart Grid: An Optimal Stopping Approach

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Abstract—The booming smart grid produces a large amount of data that should be transmitted to the utility control center (UCC), typically by means of the cellular network. This may pose a prohibitive transmission cost and choke the cellular network. As an effort to address this issue, we propose a vehicle assisted data delivery method to offload the cellular network, in which vehicles are utilized to carry and deliver the data from distributed locations to the UCC through the deployed roadside units. Two data forwarding schemes are developed based on the theory of optimal stopping rules to increase the data delivery probability. Simulation results are given to demonstrate that the proposed method can achieve high data delivery ratio through the roadside network so that it can efficiently offload the cellular network and reduce the communication cost.

I. INTRODUCTION

Recently, smart grid (SG) has attracted much attention from researchers and engineers in both power and communication fields. SG refers to a modernized and advanced power system which aims to monitor, manage and deliver electric power in a more efficient and reliable manner by incorporating state-of-the-art communication technologies into the power grid. The goal of SG is to address numerous challenges, such as generation diversification, expensive assets deployment, efficient demand response, reduction of overall carbon footprint, and so on, which can be hardly solved by the existing electricity grid [1].

SG uses smart meters and other intelligent devices densely deployed throughout the grid to monitor, manage and control the power grid. In this process, a tremendous amount of data is produced. For example, compared with the current monthly metering, the smart meters measure and store meter readings every 5 minutes, which results in a 8,000-fold increase in daily data for a utility [2]. It is predicted that the total amount of SG data for utilities will increase to over 75,200 Tbytes in 2015 [3]. Transmitting such massive data is about to swamp existing communication infrastructures. Thus, new and more capable communication infrastructures, devices and methods are required to deal with the SG data. Power Line Communication (PLC) has been considered as a candidate for SG applications [4]. PLC can provide local area network (LAN) connectivity, Internet access, and certain command and control capabilities, with a data rate of up to 200 Mb/s of state-of-the-art PLC devices. However, there are several aspects that may become impediment for the success of PLC in the market. First, PLC requires a modem for each smart meter, and the penetration of such devices is low, e.g., PLC-based deployment can only reach 1% to 5% of the meters in Europe [5]. Second, if certain problems of the power grid happen (e.g., distribution cable interruption), the communication will be unavailable. In addition, different PLC technologies are neither compatible nor interoperable with each other. In [3], a cognitive radio based hierarchical communication infrastructure is proposed to utilize wireless networks and cognitive radio to provide better QoS management for SG and facilitate to interoperate with other technologies. Cellular networks (e.g., GSM, 3G) are used for wide area communications. Sensing, transmission and control can be achieved simultaneously by the hierarchical infrastructure. However, cellular technologies such as GSM, GPRS and their peer technologies have a limited bandwidth. Moreover, the cost of using cellular networks to transmit a large amount of SG data may be prohibitive. Thus, to deal with the challenge of transferring data for SG, more flexible and efficient communication methods are expected.

Since each unit of metering data is generated and stored every 5 minutes, and for some applications, the data is required to be transmitted in half an hour to an hour (e.g. real time pricing [6]), some types of SG data have delay tolerant feature. Based on this observation, we propose a vehicle-assisted data delivery scheme, by means of the optimal stopping approach, for the SG applications as a supplement to the data delivery through the cellular networks. In the proposed system, vehicles that pass by the buildings are capable of carrying and storing the SG data. When vehicles move into the coverage of roadside units (RSUs) which are connected to the utility control center (UCC) and deployed throughout the city by utilities, they can forward the stored data to the RSUs. RSUs upload the data to the UCC through the backbone network. The vehicle-assisted data delivery has obvious advantages. It can utilize vehicular communication devices to exchange data, which uses wireless LAN that can achieve high data rate and cost much less than cellular networks. In addition, according to the mobile and distributed feature of vehicles, SG data can be collected from a very large and highly distributed scenario, which is the case of SG. In [7], an optimal probabilistic forwarding protocol in the delay tolerant network (DTN) based on optimal stopping is proposed to calculate the forwarding probabilities of each node. However, it does not consider the characteristics of vehicular environments. The optimal packet transmission in vehicular DTN is studied in [8]. An optimal decision is obtained based on the constrained Markov decision process and then the noncooperative game is employed to choose the
optimal packet transmission rate. However, in [8] packets are delivered between ad hoc nodes, while in SG, data can be delivered through any RSU.

The remainder of this paper is organized as follows: Section II describes the system model. In Section III, two data forwarding schemes based on optimal stopping rules are proposed and discussed. Section IV evaluates the performance of the proposed method. Section V concludes the paper.

II. SYSTEM MODEL

A. Network Model

We consider a city area in which RSUs are deployed by the utilities to collect the SG data. All RSUs are connected to the UCC which is responsible for collecting and managing the data from the whole SG. Entities that produce, store, and transmit the data are called data sources (DSs) of the SG, which can be houses, buildings, and distributed energy sources, etc. A DS, say $DS_i$, generates a data block (DB) every $\Delta t_{g,i}$ by aggregating the data from meters and sensors in a small geographic area (e.g., a building) using ZigBee or other home area network (HAN) technologies, and temporarily stores it. All the DBs are requested by the UCC every time interval $T$.

The vehicles equipped with communication devices, i.e., on board units (OBUs), move along the road with different velocity and direction. The remaining time for a vehicle to meet the next RSU is referred to as the meeting time of the vehicle, which is denoted by $T_m$. Due to the intermittent connectivity between vehicles and RSUs, it is considered that $T_m$ follows an exponential distribution with parameter $\mu$, i.e.,

$$T_m \sim \text{Exp}(\mu), \quad (1)$$

where $X \sim \text{Exp}(\alpha)$ denotes that random variable $X$ follows an exponential distribution with parameter $\alpha$. A similar consideration can be seen in [9]. Furthermore, vehicle arrivals at $DS_i$ is considered to follow a Poisson process $N = (N_t)_{t \geq 0}$ with parameter $\lambda_i$. It is assumed that vehicles are equipped with GPS devices and digital maps which contains the location information of the deployed RSUs. Thus, a vehicle can estimate $T_m$ at any time.

B. Communication Model

In this paper, functionally, vehicles are identified as a delivery agent of the SG data. If a vehicle arrives at $DS_i$, $DS_i$ will decide whether to choose this vehicle to deliver the DBs that are currently stored. A two-hop communication model is adopted, i.e., each DB is only forwarded to one vehicle, as shown in Fig. 1. By doing so, there is only one duplication of each DB, which yields an optimal throughput of the network [10]. During the movement along the road, the vehicle can carry DBs from different DSs of the grid. Once the vehicle contacts with an RSU, it forwards the data that it carries to the RSU as much as possible. RSUs collect data from all vehicles that move through and send the data to the UCC eventually.

Consider a typical DB, say $DB_j$. Denote by $v_j$ the vehicle which is selected to deliver $DB_j$. Denote by $t_0$ the generation instant of $DB_j$, $t_{\text{req}}$ the request instant of $DB_j$ by the UCC, and $T_i = t_{\text{req}} - t_0$ the life time of $DB_j$, as shown in Fig. 2. We also denote by $t_f$ the instant when $DB_j$ is forwarded to $v_j$, $t_r$ the instant when $v_j$ meets the first RSU after carrying $DB_j$, and $t_0$ the instant when $DB_j$ is received by the UCC. The first contact delay (FCD) of $DB_j$, denoted by $D_{F,j}$, is defined as the time duration from the generation of $DB_j$ to $v_j$’s arrival at the first RSU after carrying $DB_j$, i.e., $D_{F,j} = t_r - t_0$.

The delivery probability of $DB_j$, denoted by $P_{d,j}$, is defined as the probability that $DB_j$ can be successfully delivered to the UCC by $v_j$ before the request time $t_{\text{req}}$. Since the UCC requests the data from all DSs every $T$, the DBs which are generated within $T$ and not successfully delivered to the UCC by $t_{\text{req}}$ will be requested and transmitted through the cellular network. Thus, it is expected that the delivery probabilities of DBs are as high as possible. In this way, more data can be delivered through the roadside network, which can efficiently reduce the cost of SG utilities and offload the cellular network. In the next section, two optimal forwarding schemes based on the theory of optimal stopping rules are proposed in order to maximize the delivery probability.

III. DATA DELIVERY AS AN OPTIMAL STOPPING PROBLEM

A. Problem Formulation

There are some factors that influence the delivery probability of DBs. To successfully deliver $DB_j$, $v_j$ should contact with at least one RSU before $t_{\text{req}}$. Moreover, it is noted that $DB_j$ can be transmitted to the UCC during the first contact or the following ones, between $v_j$ and an RSU, since the vehicle may not transmit all the DBs stored to the RSU in one contact. We define $T_{EX} = t_u - t_r$, as shown in Fig. 2, which is a random variable for each DB, depending on the amount of data stored in the vehicle and the communication environment such as transmission rate and vehicle density. Therefore, the delivery probability of $DB_j$ can be presented by the probability that the summation of $D_{F,j}$ and $T_{EX}$ is no larger than $T_i$, i.e., $P_{d,j} = \Pr(D_{F,j} + T_{EX} \leq T_i)$. Since it is difficult to get the statistics of $T_{EX}$, in order to increase the delivery probability of all DBs, it is intuitive to minimize
FCD of DBs, i.e. to minimize
\[ D_{F,j} = T_{va,j} + T_{vd,j}, \]
where \( T_{va,j} = t_f - t_0 \) is the time duration from the instant when \( DB_j \) is generated to the instant when \( DB_j \) is forwarded to \( v_j \), and \( T_{vd,j} = t_f - t_f \) is the time duration it takes \( v_j \) to meet the first RSU after it carries \( DB_j \), which follows the same distribution as \( T_m \).

Choosing different vehicles to deliver \( DB_j \) leads to different \( D_{F,j} \) because both \( T_{va,j} \) and \( T_{vd,j} \) are random variables for different vehicles. However, \( D_{F,j} \) can be observed by \( DS_i \) when a vehicle arrives at \( DS_i \), based on the following observations. Obviously, \( DS_i \) knows \( T_{va} \) when a vehicle arrives. Moreover, vehicles can obtain estimated \( T_m \) and provide it to \( DS_i \) as \( T_{vd} \). Thus, the DS should choose a vehicle which offers minimum \( D_{F,j} \) as the forwarder of \( DB_j \). This problem can be formulated as an optimal forwarding scheme, based on the theory of optimal stopping rules.

In an optimal stopping problem [11], let \( G = (G_n)_{n \geq 0} \) be a sequence of random variables, which can be observed at time \( n \). For each stage \( n \), one can make a decision to stop and receive the known reward \( R_n = R(G_n) \), where \( R(G_n) \) is a function of \( G_n \), or to continue and observe \( G_{n+1} \). However, the past reward cannot be recalled. The optimal stopping problem is to stop at stage \( n \) to maximize the expected reward (or minimize the expected cost). In the following, we propose two optimal stopping based forwarding schemes in order to minimize FCD and increase the delivery probability of DBs.

B. Time Oriented Optimal Forwarding

When \( DB_j \) is generated in \( DS_i \), it is the responsibility for \( DS_i \) to choose the best time to forward \( DB_j \) to a vehicle. This forwarding scheme is called time oriented optimal forwarding (TOOF). Divide \( T_l \) into small time intervals with identical length \( \Delta t_n \), and the number of intervals is \( N_t = \lfloor \frac{T_l}{\Delta t_n} \rfloor \). Thus, \( T_{va} \) can be approximated by \( n \Delta t_n \) if \( DB_j \) is forwarded in the \( n \)-th interval. To find the optimal time interval to forward DBs is an optimal stopping problem with finite horizon \( N_t \). Such problems can be solved by backward induction [7][12].

In TOOF, the stage \( n = 1, 2, \ldots, N_t \), and thus \( DS_i \) tries to forward \( DB_j \) no later than stage \( N_t \). Therefore, we can first find the optimal forwarding rule at stage \( N_t - 1 \). Then, knowing the optimal forwarding rule at stage \( N_t - 1 \), we can find the optimal forwarding rule at stage \( N_t - 2 \), and inductively to the first stage. Let \( V_n^{N_t} \) denote the minimum expected FCD to forward \( DB_j \) starting from stage \( n \), i.e.,
\[ V_n^{N_t} = \min \{ R_n(T_{vd}), E(V_{n+1}^{N_t}) \}, \]
where \( R_n(T_{vd}) = n \Delta t_n + T_{vd} \). With at the last stage \( N_t \), \( E(V_1^{N_t}) = E(R_{N_t}(T_{vd})) = \frac{T_l}{\mu} \) inductively, at stage \( n \),
\[ E(V_n^{N_t}) = E(\min \{ R_n(T_{vd}), E(V_{n+1}^{N_t}) \}) = \int_0^\infty \min \{ n \Delta t_n + T_{vd}, E(V_{n+1}^{N_t}) \} dF_{T_{vd}}(T_{vd}) \]
where \( F_{T_{vd}}(x) = 1 - e^{-\mu x} \) is the cumulative distribution function (CDF) of \( T_{vd} \). Thus, the optimal rule at each interval (stage) \( n \), i.e., \( E(V_n^{N_t}) \) is obtained, whose value is nondecreasing with \( n \). TOOF is to forward \( DB_j \) in the first interval \( n' \) in which a vehicle can offer \( T_{vd} \leq E(V_{n'}^{N_t}) - n' \Delta t_n \).

C. Vehicle Oriented Optimal Forwarding

The time oriented forwarding scheme is to choose the best time to forward the stored DSs, which has a finite horizon. However, if we consider the forwarding problem from the perspective of individual forwarders (i.e., vehicles), the forwarding strategy is different. The forwarding scheme of choosing the optimal vehicle is called vehicle oriented optimal forwarding (VOOF). Let \( v_1, v_2, v_3, \ldots \) be the vehicles that sequentially pass by \( DS_i \) after the generation of \( DB_j \) according to Poisson arrival with parameter \( \lambda_i \), and \( X_k \) be the cost, i.e., the extra time to wait if \( v_k+1 \) is lost and \( X_0 \) be the cost, i.e., the extra time to wait if \( DS_i \) decides to wait for \( v_k+1 \) rather than forward \( DB_j \) to \( v_k \). \( X_0 \) is the time before the first vehicle comes. According to the property of Poisson process, \( \{ X_k \} \) are i.i.d. random variables following exponential distribution with the mean value \( \frac{1}{\lambda_i} \). Thus, the problem of choosing a vehicle to forward \( DB_j \) is then the optimal stopping problem with infinite horizon, in order to minimize
\[ R_k = T_{vd,k} + \sum_{n=0}^{k-1} X_n, \]
where \( T_{vd,k} \) is \( T_{vd} \) of \( v_k \).

Now suppose \( DS_i \) pays \( X_0 \) and observes \( T_{vd,1} = t_{vd,1} \). If \( DS_i \) decides to continue, then \( t_{vd,1} \) is lost and \( X_0 \) has already been paid. So it is just like starting the problem again based on the situation of infinite horizon. Thus, the problem is invariant in time [12]. Let \( V^* \) denote the optimal rule of forwarding \( DB_j \) to a vehicle. For \( DS_i \), if it decides not to choose an arbitrary \( v_k \) to forward \( DB_j \), then the minimum
Thus, by solving (6), the optimal forwarding rule follows:

\[ V^* = E(\min\{T_{vd,k} + X_k, V^* + X_k\}) \]

\[ = EX_k + E(\min\{T_{vd,k}, V^*\}) \]

\[ = \frac{1}{\lambda_i} + \int_0^V x dF_{T_{vd,k}}(x) + \int_{V^*}^{\infty} V^* dF_{T_{vd,k}}(x) \]

\[ = \frac{1}{\lambda_i} + \frac{1}{\mu} (1 - e^{-\mu V^*}), \quad (6) \]

Thus, by solving (6), the optimal forwarding rule \( V^* \) can be obtained. In VOOF, the first vehicle \( v_k \) which can offer \( T_{vd,k} \leq V^* \) will be chosen to deliver DB, i.e.,

\[ N^* = \min\{k \geq 1 : T_{vd,k} \leq V^*\}, \quad (7) \]

where \( N^* \) is the sequence number of the chosen vehicle.

### D. Expected First Contact Delay

FCD is crucial for the overall performance of the proposed data delivery method, and our optimal forwarding schemes aim to reduce FCD as much as possible. Thus in this part, we theoretically analyze the FCD that can be achieved by both forwarding schemes.

Let \( E_{FCD-TOOF} \) denote the expected FCD of DBs using TOOF, which can be represented as follows:

\[ E_{FCD-TOOF} = \sum_{i=1}^{N_t} \left( \prod_{k=1}^{N_t} P_{NT,k} \right) (1 - P_{NT,i}) E_{FCD,i}, \quad (8) \]

where \( P_{NT,k} \) is the probability that in the \( k \)-th interval there is no vehicle chosen to carry DBs and \( E_{FCD,i} \) is the expected FCD if DB is carried by a vehicle in the \( i \)-th interval. Since vehicles arrive in a Poisson process, \( P_{NT,k} \) can be calculated as follows:

\[ P_{NT,k} = \sum_{m=0}^{\infty} P_n(m) P_{NTv,k}, \quad (9) \]

where \( P_n(m) \) represents the probability that \( m \) vehicles arrive within \( \Delta t_n \) and \( P_{NTv,k} \) represents the probability that a vehicle arrives within the \( k \)-th interval, but is not eligible to carry DB, i.e., \( T_{vd} > E(V_{k+1}^N) - k\Delta t_n \).

\[ P_{NTv,k} = \Pr((T_{vd} + k\Delta t_n) > E(V_{k+1}^N)) \]

\[ = 1 - F_{T_{vd}}(E(V_{k+1}^N) - k\Delta t_n) \]

\[ = e^{-\mu(E(V_{k+1}^N) - k\Delta t_n)} \quad (10) \]

\( E_{FCD,i} \) can be calculated as the expectation of FCD in (2), i.e.,

\[ E_{FCD,i} = E(T_{vd}|T_{vd} \leq (E(V_{i+1}^N) - i\Delta t_n)) + i\Delta t_n \]

\[ = \int_0^{E(V_{i+1}^N) - i\Delta t_n} x dF_{T_{vd}}(x) + i\Delta t_n \]

\[ = \frac{1}{\mu} - (E(V_{i+1}^N) - i\Delta t_n + \frac{1}{\mu}) e^{-\mu(E(V_{i+1}^N) - i\Delta t_n)} + i\Delta t_n. \quad (11) \]

Then, we can obtain the expected FCD for TOOF using (8).

Let \( E_{FCD-VOOF} \) denote the expected FCD of DBs using VOOF. It can be calculated by the summation of the expected FCD achieved by forwarding DBs to each possible vehicle, i.e.,

\[ E_{FCD-VOOF} = \sum_{k=1}^{E_{FCD,k}} \]

\[ = \sum_{k=1}^{\infty} (ET_{va} + ET_{vd}) \cdot \Pr(k\text{-th vehicle is chosen}) \]

\[ = \sum_{k=1}^{\infty} \left( E \sum_{m=0}^{\infty} \frac{V^m}{\mu} dF_{T_{vd}}(x) \right) \]

\[ - \left[ \Pr(T_{vd} > V^*) \right]^{k-1} \cdot \Pr(T_{vd} \leq V^*) \]

\[ = \sum_{k=1}^{\infty} \left( \frac{k}{\mu} + \frac{1}{\mu} \left( V^* + \frac{1}{\mu} e^{-\mu V^*} \right) e^{-k(1-\mu V^*)} (1 - e^{-\mu V^*}) \right) \]

Recall that \( X_m \) is the inter-arrival time between the \( m \)-th and the \((m+1)\)-th vehicle, which are i.i.d. exponential random variables with the mean value \( \frac{1}{\lambda_i} \).

### IV. Evaluation of Performance

In this section, we evaluate the performance of the proposed vehicle-assisted data delivery method for SG using simulation experiment. An urban scenario is considered with randomly deployed RSUs. DSs generate a DB every \( \Delta g \) minutes and the request interval for DBs is \( T = 30 \) minutes.

Simulation and analytical results of FCD are shown in Fig. ??, in Fig. 4(a), the impact of the vehicle arrival rate \( \lambda \) is shown. With the increase of \( \lambda \), the forwarding probability in former intervals in TOOF increases, whose optimal rules are smaller than those of later intervals, leading to smaller FCD. In VOOF, the increase of \( \lambda \) reduces the time for DSs to wait for the eligible forwarding vehicle, and thus the FCD is reduced. In Fig. 4(b), the impact of mean inter-meeting time \( \frac{1}{\mu} \) is shown. In both TOOF and VOOF, a smaller value of \( \frac{1}{\mu} \) indicates that the value of \( T_{vd} \) is smaller, which leads to a smaller value of FCD. The reason that VOOF can achieve smaller FCD than TOOF is that in TOOF, some intervals are wasted because there is no vehicle arrives in these intervals.

The delivery ratio of DBs is shown in Fig. 3 and Fig. ??, we compare the performance of TOOF and VOOF with a simple scheme called best effort (BE), in which the first vehicle with \( T_{vd} < t_{req} - t_f \) is chosen as forwarder of DBs. BE is to guarantee that vehicles carrying DBs can contact at least one RSU before the request time, i.e., \( t_{req} \). However, BE fails to consider \( T_{EX} \), which is the extra time for the utility to actually get a DB after the vehicle that carries the DB arrives at the first RSU, as described in Section III-A.

Fig. 4(c) shows the mean FCD w.r.t. the DB life time \( T_l \). It is shown that both TOOF and VOOF can achieve lower FCD than BE, because BE only guarantees that vehicles carrying DBs meet an RSU before the request time, and thus vehicles which offer long FCD may be also chosen. In Fig. 4(d), delivery ratio of DBs w.r.t. \( T_l \) is presented. It can be seen that DBs with larger \( T_l \) have higher delivery ratio because the delivery probability, i.e., \( \Pr(D_F + T_{EX} < T_l) \) is larger.
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sent through the cellular network. To enhance the data delivery
data to the utility control center as much as
smart grid has been proposed. Vehicles are utilized to carry
and deliver SG data to the utility control center as much as
possible, in order to reduce the amount of data that has to be
sent through the cellular network. To enhance the data delivery
probability through vehicles, two forwarding schemes based
on the optimal stopping theory have been proposed. We have
shown some theoretic results, and evaluated the performance of
the proposed schemes through simulation experiment. It
has been shown that TOOF and VOOF outperform the best
effort scheme, and in some cases, nearly 70% of SG data can
be delivered using the proposed method, which can greatly
reduce the cost of utilities, and offload the cellular network.

With $T_i = 5\ \text{min}$, the delivery ratios of all the three schemes
are very low because $T_{EX}$ is very likely larger than $T_i$, and
thus few DBs can be delivered to the UCC. Fig. ?? shows
the overall delivery ratio of DBs w.r.t. $\lambda$ and $\frac{1}{\mu}$. The overall
delivery ratio is the average delivery ratio of DBs over all $T_i$.
With the increase of $\lambda$ and decrease of $\frac{1}{\mu}$, FCD decreases and
thus $\Pr(D_F + T_{EX} < T_i)$ gets larger, and then the overall
delivery ratio increases.

V. CONCLUSION

In this paper, a vehicle-assisted data delivery method for
smart grid has been proposed. Vehicles are utilized to carry
and deliver SG data to the utility control center as much as
possible. The overall database delivery ratio increases.

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