Infrastructure Aided Networking and Traffic Management for Autonomous Transportation

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***Abstract*—Traffic management mechanisms for autonomous vehicular transportation systems are designed to regulate vehicular topological layouts and mobility patterns to form robust data communication networks while guaranteeing vehicular throughput rates. To enhance the performance of the underlying wireless communications networking operations, this system would be aided by the deployment of an information network infrastructure that consists of Road Side Units (RSUs). In this paper, we study the design of an RSU-aided autonomous vehicular network that incorporates both data networking and traffic management dimensions. We investigate the inter-relationships that characterize the joint design of vehicular ad hoc networking control mechanisms and cost-effective RSU backbone network. We configure vehicles into platoon structures in aiming to guarantee a robust dissemination of data message flows. An efficient algorithm is developed to determine the optimal settings of platoon parameters and RSU locations across a highway. The result is used to demonstrate the fundamental design tradeoffs to be made when considering performance metrics that involve vehicular throughput rates, infrastructure deployment costs, and the reliability of wireless communications networking.**

I. Introduction

The market of autonomous vehicles is expected to experience a drastic growth. The use of such vehicles is foreseen to improve in-road safety and alleviate traffic jams. For this purpose, vehicles are designed to gather information from surrounding areas via built-in sensors and/or relying on information provided by other vehicles. Reliable vehicular ad hoc networks (VANETs) [1] are generally integrated in the design of autonomous transportation system.

The employment of autonomous vehicles has introduced new dimensions that are incorporated in the system's design to achieve prescribed system performance. In contrast with approaches that have been employing statistical models to characterize moving patterns of human-driven cars [2], [3], [4], we propose to autonomously regulate vehicular mobility patterns. With the aid of Cooperative Adaptive Cruise Control (CACC) systems [5] and the integration of Vehicle-to-Vehicle (V2V) communication networks, vehicles are able to coordinate and configure their mobility patterns, speeds and distance spacings. For this purpose, in moving across a highway, vehicles are often grouped into platoons [6], [7].

Configuring vehicles to move in groups often serves to effectively alleviate traffic jams and improve fuel efficiency [8]. Such configurations are also advantageous in forming a V2V data communications network. Within a platoon, one can readily employ a centralized and reliable communication protocol, such as Time Division Multiple Access (TDMA), which is maintained and dynamically controlled through an intra-platoon management procedure. We demonstrated in a previous work [9] that by properly selecting platoon configuration parameters, the aggregated interference level that impacts the operation of the V2V wireless communications network can be effectively managed and often significantly reduced, improving the data throughput performance of the system. Additional control signaling is however required to provide for the synchronization and coordination of platoon vehicles. Consequently, one must incorporate limitations in the availability of bandwidth resources affecting control channel capacity, and thus restrict the platoon's spatial data messaging and control coverage span, and limit the number of vehicular members of a platoon. For cases that involve wide dissemination of message flows that must traverse multiple platoons, inter-platoon transmissions often become critical throughput bottleneck factors [9].

To facilitate message dissemination over a VANET system and to bridge the link gaps that may exist in communicating among vehicles across platoons, the deployment of Road Side Units (RSUs) is often considered as a promising solution. RSUs are inter-connected to each other through a high speed, generally wired, backbone core network. In accessing RSUs and in disseminating message flows across the core network, when feasible, one can enhance in a significant manner the capacity of the system to distribute message flows over wide distance ranges. Several research studies [10], [11], [12] have been published in investigating cost-effective RSU deployment strategies, used to guarantee delay-throughput performance requirements through the employment of a minimal number of RSUs. Yet, these works either assume statistical traffic models or use real world human-driver based data statistics in modeling the underlying vehicular mobility processes. The potential performance improvements achievable by regulating the vehicular topology are yet to be studied and exploited.

In this paper, we investigate the joint design of vehicular traffic regulation mechanisms and RSU deployment strategies. To attain a cost-effective RSU deployment solution, we aim to maximize the distance between RSUs while configuring vehicles into platoons in a manner that serves to guarantee a minimum level of vehicular throughput rate and to limit the probability of using unreliable inter-platoon V2V links for message disseminations. We consider the dissemination of heterogeneous message types among highway vehicles, as they are differentiated by their targeted message spans.

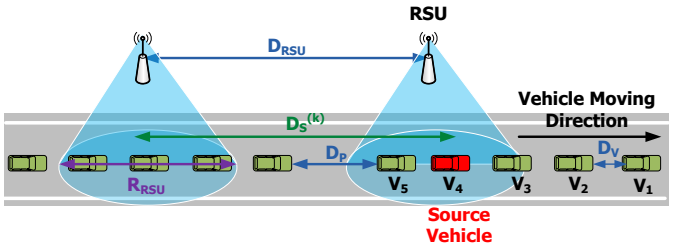

Fig. 1. RSU-assisted VANET configurations ($N_V = 5$).

An optimization framework is formulated and a polynomial time algorithm is proposed. It involves the solution of a sequence of linear programming sub-problems. The underlying design tradeoffs in achieving high data networking reliability, low RSU cost, and high vehicular throughput rate, are well demonstrated.

The paper is organized as follows. In Section II, we introduce our system model, modeling the underlying platoon configurations and RSU deployments. The optimization framework is formulated accordingly. In Section III, we present a computationally efficient algorithm for solving the optimization problem. Numerical results are illustrated in Section IV. The paper is concluded in Section V.

II. System Model

A. Platoon Configuration

In an autonomous highway system, the number of vehicles traveling in a segment of a highway can be effectively controlled through an on-ramp access regulation, often identified as *Traffic Density Control* [13]. Accordingly, we assume that a total number of N vehicles are admitted to travel at a constant speed v over a single lane highway segment of length L. Admitted vehicles are regulated to form N_P platoons. For simplified analysis, we assume each platoon to consist of an equal number of $N_V = \frac{N}{N_P}$ vehicles and N to be an integral multiple of N_P.

The intra-platoon spacing D_V is defined as the distance between neighboring vehicles belonging to the same platoon. The value of D_V is regulated to be the same for all platoons. Distances between any two neighboring platoons, the inter-platoon distances, are denoted as D_P. They are also regulated to assume the same values for all neighboring platoons. An illustrative example of the platoon structure of interest is shown in Fig. 1. In this case, D_P is calculated as:

$$D_P = \frac{L - N_P[D_V(N_V - 1) + sN_V]}{N_P}, \tag{1}$$

where s is the length of each vehicle. In the following, we assume $s = 0$ for formulation simplicity. Nonzero values of s only add a constant term over the derived solutions, which is a straightforward extension. We also assume that $D_V \leq D_P$. In addition, the selection of D_V must satisfy a safety constraint. To account for safety spacing margins that are required for a proper reaction to a sudden stop of a vehicle by vehicles hat follow, we set D_V to a value that is longer than the stopping distance of the immediate upstream vehicle. That is,

$$\frac{v^2}{2u} \leq D_V, \tag{2}$$

where u is the vehicular deceleration level.

In order to manage and coordinate the configuration of vehicles within their platoon, control messages are exchanged among platoon members. As the number of platoon members N_V increases, the control data traffic increases accordingly. Also, under longer D_V spacing range values, such control message flows may not always be successfully broadcasted across the platoon. Accordingly, we assume that the maximum allowable platoon span $D_V(N_V - 1)$ is lower than or equal to R_c that limits the range across which coordination among platoon members must be assured.

B. Message Categories

The message flow types that are disseminated among highway vehicles are classified into a total of K types, corresponding to distinct application types. Messages of type-k generated by a given source vehicle are required to be disseminated and received by vehicles within a targeted span $D_s^{(k)}$ downstream the source vehicle. A type-k message is randomly generated by a vehicle with probability q_k. Without loss of generality, we assume that $D_s^{(k)} \leq D_s^{(k+1)}$, $k = 1...K-1$. This model is consistent with that described for the intelligent transportation system by the U.S. Department of the Transportation [14]. The latter model identifies message types such as emergency report, lane merging warnings, and traffic condition updates.

C. RSU Deployment

Road Side Units (RSUs) are assumed to be deployed uniformly along the highway with an inter-RSU distance equal to D_{RSU}. Each RSU is able to cover vehicles within a range R_{RSU} as illustrated in 1. RSU deployment is used to facilitate message transport over VANET, especially when such messages are required to be sent across multiple platoons. As demonstrated in [9], inter-platoon links form bottleneck factors in the determination of the data throughput capacity available for the dissemination of message flows among vehicles, induced by the occurrence of longer inter-platoon ranges and by the lack of coordination management across platoons. Consequently, we use in this paper a model that serves to guarantee the reliability of a VANET system by restricting the probability that disseminated message flows need to traverse inter-platoon links. We require the latter probability to be lower than a threshold Ψ value.

The probability that a message needs to be sent from the platoon associated with the source vehicle to the neighboring platoon by using an inter-platoon V2V link is calculated as

$$P_{inter\_V2V} = P_{iso} \sum_{k=1}^{K} P_{inter}^{(k)}, \tag{3}$$

where P_{iso} is the platoon isolation probability; i.e. the probability that all the vehicles in a platoon are not covered by any RSU. $P_{inter}^{(k)}$ is the probability that a type-k message, with

span $D_s^{(k)}$, has to be disseminated across multiple platoons. These quantities are calculated as follows:

$$P_{iso} = 1 - \min\Big\{\frac{D_V(N_V-1)}{D_{RSU}-R_{RSU}}, 1\Big\}. \tag{4}$$

$$P_{inter}^{(k)} = \frac{\max\{\min\{1+\lfloor\frac{D_s^{(k)}-D_P}{D_V}\rfloor, N_V\}, 0\}}{N_V}. \tag{5}$$

D. Problem Formulation

To determine a cost efficient RSU deployment strategy while guaranteeing both data network and vehicular network performance rates, we form the following optimization problem **(P-COST-EFF-RSU)**. The objective function aims to maximize the distance between RSUs.

(P-COST-EFF-RSU)

$$\underset{D_{RSU},D_V,D_P,v,N_V}{\text{maximize}} \quad D_{RSU}$$

subject to

$$P_{iso}\sum_{k=1}^{K} P_{inter}^{(k)} \le \Psi \tag{C-1}$$

$$\frac{D_V(N_V-1)}{D_{RSU}-R_{RSU}} \le 1 \tag{C-2}$$

$$D_P = \frac{LN_V}{N} - D_V(N_V-1) \tag{C-3}$$

$$D_V = \frac{v^2}{2u} \tag{C-4}$$

$$D_V(N_V-1) \le R_c \tag{C-5}$$

$$v \ge v_{min} \tag{C-6}$$

$$D_P \ge D_V \ge 0 \tag{C-7}$$

$$D_{RSU} \ge 0 \tag{C-8}$$

The constraint requirements are explained as follows:

- (C-1) Link reliability constraint
- (C-2) The platoon length is not longer than the uncovered region between two neighboring RSUs. If the equality holds, messages can be transported across the network without using inter-platoon links.
- (C-3) The definition of inter-platoon distances
- (C-4) Safety constraint
- (C-5) Platoon coordination range limit
- (C-6) Minimum vehicular speed requirement
- (C-7) Inter-platoon distance is not shorter than the intra-platoon distance.
- (C-8) Nonnegativity of inter-RSU distances

It is observed that the quadratic expression on the left hand side of (C-1) results in non-convexity of **(P-COST-EFF-RSU)**. In the following section, we present a polynomial time algorithm to solve **(P-COST-EFF-RSU)** by solving a sequence of linear programming problems.

III. Proposed Algorithm

We first identify two parameters $\underline{K}$ and $\overline{K}$ that group inter-platoon transmission probabilities of different message types into three categories:

$$P_{inter}^{(k)} = 0 \quad \forall k = 1...\underline{K} \tag{I-1}$$

$$0 < P_{inter}^{(k)} < 1 \quad \forall k = \underline{K}+1...\overline{K} \tag{I-2}$$

$$P_{inter}^{(k)} = 1 \quad \forall k = \overline{K}+1...K \tag{I-3}$$

Accordingly, (C-1) in **(P-COST-EFF-RSU)** can be rewritten as

$$[D_{RSU}-R_{RSU}-D_V(N_V-1)]\times \left[\sum_{k=\underline{K}+1}^{\overline{K}} q_k\left(1+\Big\lfloor\frac{D_s^{(k)}-D_P}{D_V}\Big\rfloor\right) + \sum_{k=\overline{K}+1}^{K} N_V q_k\right] \le \Psi N_V(D_{RSU}-R_{RSU}) \tag{C-1-1}$$

The following observations can also be deduced from **(P-COST-EFF-RSU)**:

- (C-1): The left hand side of the inequality is an increasing function of D_{RSU}.
- (C-2): holds if $D_{RSU} \ge D_V(N_V-1)+R_{RSU}$.
- (C-3) - (C-8): Constraints independent from the choices of D_{RSU}

Hence, we can perform a binary search over D_{RSU} to find the largest value of D_{RSU} that satisfies (C-1) - (C-8). We apply a change of variables by setting $g \triangleq \frac{D_{RSU}-R_{RSU}}{D_V}$. Then, $D_{RSU} = R_{RSU} + gD_V$. We also approximate the floor function by using that $\lfloor x \rfloor \le x$. As a result, the following constraint is tighter than (C-1):

$$[g-(N_V-1)]\times \left[\sum_{k=\underline{K}+1}^{\overline{K}} q_k(D_s^{(k)}-D_P+D_V) + D_V N_V \sum_{k=\overline{K}+1}^{K} q_k\right] \le \Psi g N_V D_V \tag{C-1-2}$$

For a fixed value of N_V and g, the constraint (C-1-2) is a linear constraint in D_V and D_P.

Hence, for a fixed value of g, N_V, $\underline{K}$, and $\overline{K}$. we solve the following linear programming problem:

(P-MAX-DV)

$$\underset{D_V,D_P,v}{\text{maximize}} \quad D_V$$

subject to

$$g \ge N_V - 1$$

$$D_s^{(k)} \le D_P - \epsilon,\ k = 1...\underline{K} \tag{I-1'}$$

$$D_P \le D_s^{(k)} \le (N_V-1)D_V + D_P,\ k = \underline{K}+1...\overline{K} \tag{I-2'}$$

$$(N_V-1)D_V + D_P + \epsilon \le D_s^{(k)},\ k = \overline{K}+1...K \tag{I-3'}$$

(C-1-2)

(C-3)-(C-7) of **(P-COST-EFF-RSU)**

The objective function D_{RSU} is replaced by $R_{RSU}+gD_V$. For a fixed g value, maximizing D_{RSU} is thus equivalent to maximizing D_V. Note that constraints (I-1') - (I-3') are derived from (I-1) - (I-3). The positive scalar ϵ is introduced in (I-1') and (I-3') to handle the strict inequalities in (I-1) and

(I-3).

In addition, to incorporate the possibility that all the constraints are met even when no RSU is deployed, we consider the solution of following feasibility problem:

(P-NO-RSU)

$$\underset{D_V, D_P, v}{\text{maximize}} \quad 1$$

subject to

$$\left[\sum_{k=\underline{K}+1}^{\overline{K}} q_k (D_s^{(k)} - D_P + D_V) + D_V N_V \sum_{k=\overline{K}+1}^{K} q_k \right] \leq \Psi N_V D_V$$

(I-1')-(I-3') of **(P-MAX-DV)**

(C-3)-(C-7) of **(P-COST-EFF-RSU)**

Similar to **(P-MAX-DV)**, **(P-NO-RSU)** can be solved efficiently using linear programming for a fixed value of g, N_V, $\underline{K}$, and $\overline{K}$. Consequently, the following algorithm is proposed for solving **(P-COST-EFF-RSU)**:

Algorithm 1

Initialization: $D^*_{RSU} = 0$;
Initialization: $\mathbf{N_V} \triangleq \{\text{Set of } N_V \text{ values}\} \subseteq \{1...N\}$;
Initialization: $n = 1$;
Iteration:

1: **repeat**
2: $N_V = \mathbf{N_V}[n]$
3: $\underline{K} = K$
4: **repeat**
5: $\overline{K} = \underline{K} - 1$
6: **repeat**
7: Solve **(P-NO-RSU)**
8: **if** feasible **then** $D^*_{RSU} = \text{Inf}$;
9: return
10: **else**
11: $g_{min} = N_V - 1$;
12: $g_{max} = G$;
13: **repeat**
14: $g = \frac{g_{min} + g_{max}}{2}$;
15: Solve **(P-MAX-DV)**
16: **if** feasible **then**
17: $D^*_{RSU} = \max\{R_{RSU} + gD_V, D^*_{RSU}\}$
18: $g_{min} := g$;
19: **else**
20: $g_{max} := g$;
21: **end if**
22: **until** $g_{max} - g_{min} < \mu$
23: **end if**
24: $\overline{K} := \overline{K} - 1$
25: **until** $\overline{K} = 0$
26: $\underline{K} := \underline{K} - 1$
27: **until** $\underline{K} = 0$
28: $n := n + 1$
29: **until** $n = \text{length}(\mathbf{N_V}) + 1$

The outer-most loop iterates through all possible values of platoon sizes N_V (Line 1). The two inner loops (Line 4 and Line 6) iterate through all possible combinations of $\underline{K}$ and $\overline{K}$. In Lines 7-9, we first examine the possibility of the existence of a feasible solution when no RSU is deployed. If a feasible platoon configuration can be obtained by solving **(P-NO-RSU)**, this solution is returned as the optimal solution. Otherwise, we perform in Lines 11-23 a binary search over the values of D_{RSU} through the variable g. The values of g_{min} and g_{max} specify the lower and upper bounds for the search region, respectively. Initially, we set $g_{min} = N_V - 1$ and $g_{max} = G$, where G is generally chosen to be a large number (e.g., a large integer value). If a feasible platoon configuration can be obtained for a given D_{RSU}, we examine a D_{RSU} set with larger values, and vice versa. The search process is terminated when the size of the search region is lower than a tolerance level μ.

IV. Performance Evaluation

In this section, we use the proposed algorithm to obtain solutions that illustrate the characteristics of the core network required to support the V2V wireless network associated with the autonomous transportation system. The length of the highway segment of interest is 5 (km). Two different message spans are investigated: $D_s^{(1)} = 250$ (m) and $D_s^{(2)} = 1500$ (m). Two different message-type distributions are studied: (1) $(q_1, q_2) = (0.2, 0.8)$ (2) $(q_1, q_2) = (0.5, 0.5)$. The deceleration level is set to 5 (m/s^2). The value of ϵ in (I-1') and (I-3') is set to 10^{-5}. The tolerance level μ for the binary search procedure is equal to 0.01.

A. RSU coverage vs. vehicular throughput

We set the system parameters to $N = 96$ and $R_c = 360$ (m). The ensuing system performance behavior is illustrated in Fig. 2. The top-left sub-figure shows the minimum RSU coverage required to satisfy the prescribed probability Ψ of using inter-platoon links. The top-right, the bottom left, and the bottom right sub-figures show the corresponding optimal D_V, N_V, and D_P values, respectively. The RSU coverage is calculated as $\frac{R_{RSU}}{D_{RSU}}$.

It is observed that as the vehicular speed decreases, the required RSU coverage for a fixed value of Ψ, decreases as well. At the lowest speed level $v_{min} = 30$ (km/hr), no RSU coverage is required. Under lower speeds, the platoon span is reduced, as shorter D_V values can be maintained, so that the inter-platoon distance tends to be longer than the required message dissemination range and it is not necessary to be aided by a core network. In turn, to maintain a higher speed, a longer D_V value is required. Subsequently, due to the restriction imposed on the platoon coordination range R_c, fewer vehicles are assigned as members of a single platoon. As a result, a larger number of platoons (over the highway segment of span L) is synthesized, so that the probability of using inter-platoon links increases. Consequently, a higher RSU density is required. These observations lead to the underlying "RSU coverage vs. vehicular throughput" tradeoffs. Note that the highway vehicular throughput is defined as $\frac{Nv}{L}$. Hence, under fixed

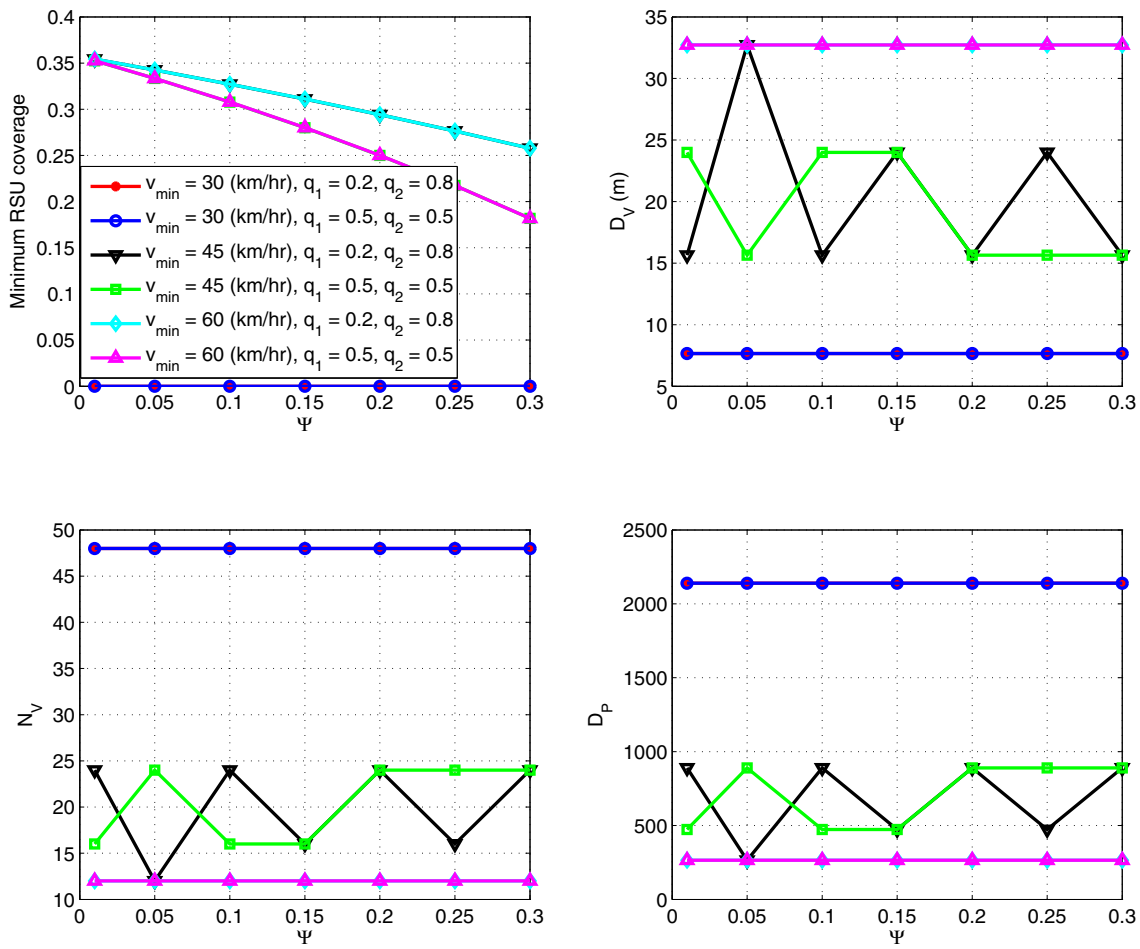

Fig. 2. Optimal RSU deployment and VANET configurations ($N = 96$, $R_c = 360(m)$).

values of N and L, the vehicular throughput, representing the capacity rate of the highway in support a flow of vehicles, is proportional to the vehicular speed.

As the speed limit is increased to $v_{min} = 45, 60$ (km/hr), the minimum RSU coverage level is noted to be insensitive to the speed value v_{min}. It is observed to be dominated by the message type distribution. This can be explained by again noting that for such higher v_{min} values, a smaller number of vehicles would be grouped into a single platoon, resulting in shorter inter-platoon distances and a higher probability of inter-platoon communications, $P_{inter}^{(k)}$. Under such conditions, the RSU coverage requirement would be significantly reduced only if we are required to span a relatively shorter average dissemination range, preferring the lower inter-platoon transmission probability $(q_1, q_2) = (0.5, 0.5)$.

B. Platoon configuration vs. reliability constraint Ψ

It is observed that when the vehicular speed is constrained by a low ($v_{min} = 30$ (km/hr)) level, the use of RSU coverage is often not essential. In turn, under higher speed levels, such as setting($v_{min} = 60$ (km/hr)), to guarantee the prescribed Ψ level, the use of RSU coverage would be often needed. For the former,46 vehicles are allowed to group into a single platoon, resulting in a long inter-platoon spanning distance (2140 (m)). In this case, no inter-platoon transmission is required, so that any specified Ψ level is met. For the latter, a larger value of D_V and thus a lower value of N_V are required, noting that the spanning range of a platoon must be limited due to the coordination range constraint. Therefore, the inter-platoon distance is now reduced. Consequently, to meet the link reliability constraint Ψ, it is now necessary for the design to provide wider RSU coverage.

When setting an intermediate vehicular speed ($v_{min} = 45$ (km/hr)), the optimal configuration is sensitive to the choice of Ψ. For a low Ψ value, RSU coverage must be high and D_V must be kept low to reduce the $P_{inter}^{(k)}$ value. As the value of Ψ increases, D_V can be set to a larger value. However, when we keep increasing the Ψ level, a lower value of D_V must again be chosen to restrict the $P_{inter}^{(k)}$ level. The preferred D_V values tend to oscillate for different values of Ψ. However,

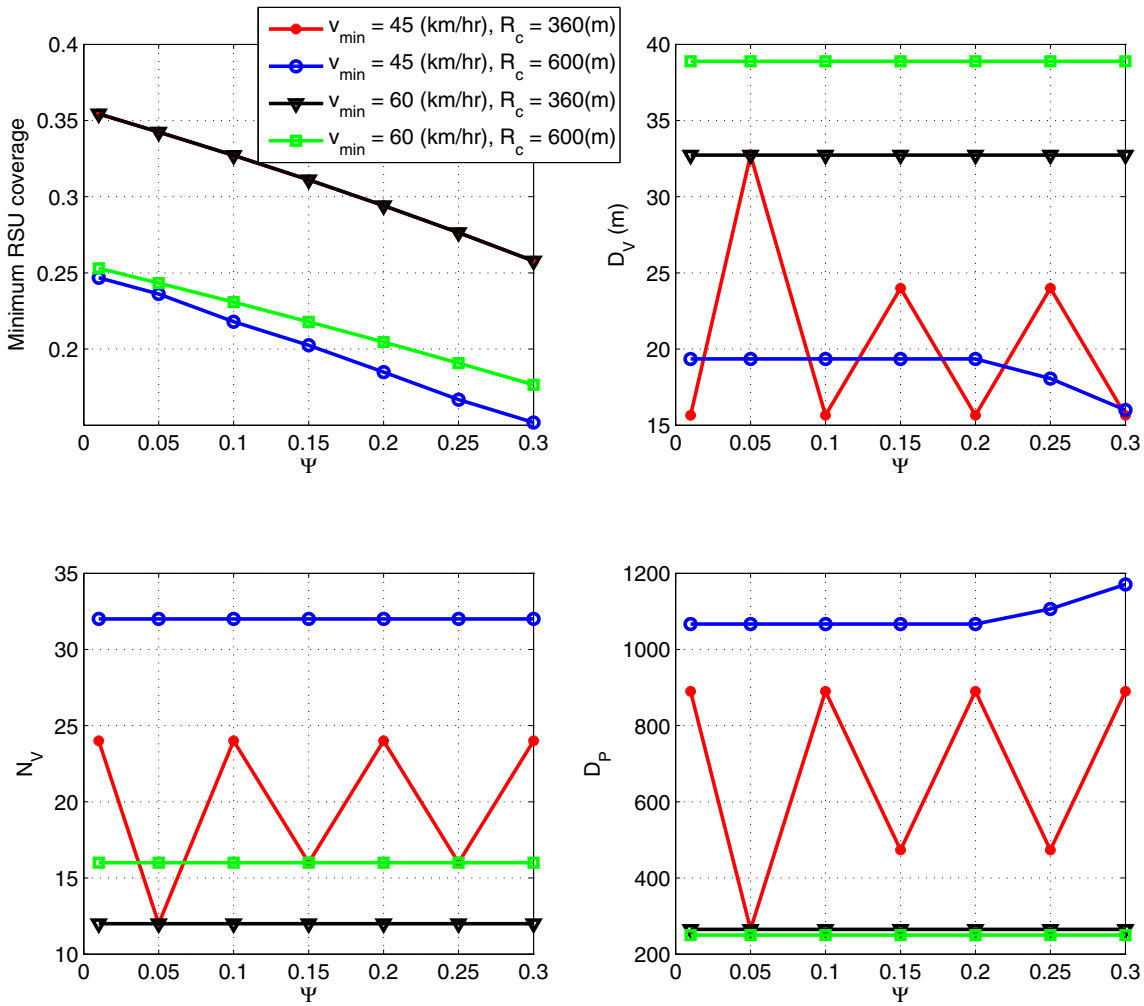

Fig. 3. Optimal RSU deployment and VANET configurations under different platoon coordination ranges R_c ($N = 96$, $q_1 = 0.2$, $q_2 = 0.8$).

we note that by searching over a larger solution space of D_V when $v_{min} = 45$ (km/hr), compared with that for $v_{min} = 60$ (km/hr), we do not reduce the RSU cost significantly. For $v_{min} = 45$ (km/hr), we can still obtain similar RSU coverage requirement by using the platoon configuration obtained for the $v_{min} = 60$ (km/hr) case.

C. Impacts of platoon coordination ranges

In Fig. 3, we illustrate the optimal RSU and platoon configurations to be synthesized under different coordination range R_c levels, assuming $N = 96$. It is noted that under a longer coordination range, the minimum RSU coverage required to achieve a given link reliability constraint Ψ is reduced since the inter-platoon transmission probability is reduced. For $v_{min} = 45$ (km/hr), we observe that by increasing the coordination range, we achieve a platoon configuration that is more robust to the Ψ values that are selected. Such an observation is explained by noting that for a longer coordination range, such as $R_c = 600$ (m), we are able to configure the system so that we achieve an inter-platoon distance that is longer than 1000 (m) by configuring each platoon to contain a higher number of vehicles. Consequently, we can significantly reduce the $P_{inter}^{(k)}$ level for all values Ψ and the optimal platoon configurations become generally much less sensitive to the prescribed Ψ level. The designer must however consider the tradeoffs that exist between RSU deployment costs and intra-platoon signalling overhead rate induced bandwidth resource costs.

V. Conclusions

In this paper, we propose a cost-effective core network that employs Road Side Units to provide access to highway vehicles to/from the core network. We develop and study an algorithm that solves for a RSU deployment strategy that maximizes the inter-RSU distances, under prescribed vehicular throughput and data network reliability levels. Highway vehicles are configured into platoons with properly chosen parameters. The optimization framework demonstrates the funda-

mental tradeoffs to be considered in designing an autonomous transportation system that provides for the dissemination of data flows through the use of a hybrid wireless network. We show that to attain a higher vehicular throughput rate, while guaranteeing a proper level of communications networking rate, the core network must be designed to provide for a higher level of access coverage to highway vehicles. The proposed framework is readily expandable to accommodate different choices of networking protocols and traffic regulation mechanisms to explore new tradeoffs in jointly design the autonomous transportation system with the hybrid autonomous VANET systems.

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