Analysis of Aggregated Power Level and Rate-Power Control Designs for Status Update Messages in VANETs

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***Abstract*—In vehicular ad-hoc networks, status update messages are used to disseminate vehicle state information so that each vehicle can track movements of its neighbors. In this paper, we focus on the aggregated power level from this kind of active safety messages and its impact on DSRC channel quality. With macroscopic model and LWR (Lighthill-Whitham-Richards) PDE, we show how the probability distribution of aggregated power level propagates along time and space. Based on our analysis, several rate-power control ideas for status update messages are discussed. In addition, microscopic traffic/network simulation results show that our proposed rate-power control algorithm can reduce channel interference and thus enhance tracking accuracy.**

I. Introduction

An intelligent vehicular network is composed of cars equipped with IEEE 802.11p [16] transceivers and sufficient computing power for intelligent functionalities. Specifically, VANETs (Vehicular Ad-Hoc Networks) have been identified as the key platform to enable various ITS (Intelligent Transportation System) applications. For this purpose, FCC has allocated 75 MHz bandwidth around 5.9 GHz [18]. Different from traditional ad hoc networks, which focus more on throughput enhancement or network connectivity, e.g. [2], [7], an important application of VANETs is safety enhancement with time critical one-to-many inter-vehicle communication. This requires strategies different from traditional methods of maximizing throughput or maintaining network connectivity.

It has been suggested by VSCC (Vehicle Safety Communications Consortium) that each vehicle should broadcast its own state information, e.g. position, speed, heading, periodically to facilitate safety applications. VSCC reports a list of suggested active safety applications and their requirements in [19]. The purpose of this kind of state update messages is for a subject vehicle to disseminate its state information so that its neighboring vehicles can collect this information and track its movement. Essentially, every car tracks neighboring cars while broadcasting its own state information at the same time. Based on this proximity-awareness, a variety of active safety applications can be provided to the driver, e.g. collision avoidance and lane change warning. See [9], [10], [11], [12], [14], [22] for engineering work in this aspect.

Besides status update messages, there still are other kind of messages co-existing in DSRC channel. For example, when a crash happens and blocks the highway, an event-driven message will be initiated by the crashed vehicle to inform other drivers of this hazardous situation. To ensure the delivery of such a time-critical warning message, the aggregated power level of status update messages must be controlled at all locations for all time. Otherwise, it would create severe interference to other messages, especially ones with higher priorities.

From a macroscopic point of view, i.e. when the number of vehicles is large enough to be treated as a fluid system, this aggregated power level also creates interference among status update messages themselves. This interference then determines the SIR (signal-to-interference ratio) and BER (Bit Error Rate) of transmitted messages. If this aggregated power level is too high, i.e. SIR is too low, transmitted messages will be corrupted with high probability.

The above understanding motivates our study on the aggregated power level of status update messages and its impact on DSRC channel quality. In this paper, we will first model the macroscopic behavior of aggregated power level if uniform Tx (transmission) rate-power pair is used by each car. Based on that analysis, the upper bound on rate-power product is derived and several variable Tx rate-power control designs are discussed. Finally, we propose our own design and verify its performance by microscopic traffic/network simulations.

The organization of this paper is the following: Section II is devoted to the analysis of aggregated power level if uniform Tx rate-power is used for status update messages. Section III presents variable Tx rate-power control ideas and our proposed algorithm to maintain DSRC channel quality and enhance tracking accuracy. Simulation results are presented in both Section II and III. Section IV concludes this paper.

II. Uniform Transmission Rate-Power for Status Update Messages

As mentioned previously, the aggregated power level of these status update messages must be controlled; otherwise, it becomes background interference to other messages and degrades overall DSRC channel quality. In this section, we will model the macroscopic behavior of aggregated power level if uniform Tx rate-power policy is used on each vehicle. This simple broadcast scheme is suggested by [19].

A. Preliminaries and Problem Formulation

In this subsection, we describe our problem formulation as the basis for later analysis. To get an insight into this problem, we simplify the model for vehicular channel access behaviors and avoid the complexities involved in modeling the 802.11 CSMA/CA mechanism [16]. Our simplified model uses two design parameters: Tx probability (rate) and Tx power. Our

Research supported in part by General Motors R & D Center through contract #TCS 70709 to U. C. Berkeley. The views expressed here are those of the authors and not of the research sponsors. The authors are with Institute of Transportation Studies, University of California, Berkeley, CA, 94720-1720. Contact: chingling@berkeley.edu

analysis can be extended with the help of Bianchi's Markov chain model [8], which relates CSMA/CA parameters to Tx probability mathematically.

Let $x \in \mathbb{R}$ represent the location on 1-D highway, $t \in \mathbb{R}$ represent the time, and $c(x,t)$ be the aggregated power level at location x and time t. Let $\rho(x,t)$ and $q(x,t)$ present the density and flow of vehicular traffics at location x and time t. Following Greenshield's assumption [4], flow is a function of density, which is usually denoted as $q(\rho(x,t))$. Note that, for convenience, sometimes we fix time index t (and thus drop it) and use $c(x)$ for the aggregated power, $\rho(x)$ for the density of vehicles. In addition, let $\lambda(x)$ be Tx probability and $\pi(x)$ be Tx power used by each vehicle at location x.

A DSRC channel propagation model (1) is used in our analysis. Given a pair of sender-receiver, if the sender transmits with power τ, given the Euclidean distance d (separation of sender-receiver), the received power ω is a random variable:

$$\omega(\tau,d) =^d \phi \times \frac{\tau}{d^\gamma} \times Z_1 \times Z_2 \quad (1)$$

where ϕ is a constant, path loss exponent $\gamma \geq 2$ models the energy dissipation w.r.t separation $d > 0$, random variables Z_1 and Z_2 represent shadowing and multi-path effects respectively.[1]

In the literature, Z_1 is usually modeled as a log-normal random variable while Z_2 has Rayleigh or Nakagami distribution; see [9], [15]. Furthermore, Z_1 and Z_2 are assumed to be independent since they come from different physics phenomena. Path loss exponent γ may vary greatly from a suburban highway to an urban canyon. In [15], a value of γ from 2 to 3 is derived from empirical data in urban environment.

When there are multiple senders, aggregated power level at location x is the superposition of received power from each sender calculated independently by (1). With $\lambda(x)$ and $\tau(x)$, the expected aggregated received power can be calculated by

$$E[c(x)] = \int_{-\infty}^{\infty} \rho(x+y)\lambda(x+y)E[\omega(\tau(x+y),y)]dy. \quad (2)$$

Let $\Phi \equiv \phi \times E[Z_1 Z_2]$, which can be measured empirically. By plugging it in (2),

$$E[c(x)] = \Phi \times \int_{-\infty}^{\infty} \frac{\rho(x+y)\lambda(x+y)\tau(x+y)}{y^\gamma} dy. \quad (3)$$

Given (3), if one wants to *probabilistically* control the aggregate power under a pre-defined threshold $\Omega > 0$ for location x, by Markov's inequality [1],

$$\Pr(c(x) \geq \Omega) \leq \frac{E[c(x)]}{\Omega}. \quad (4)$$

One can properly choose $\lambda(x)$ and $\tau(x)$ so that $E[c(x)] < \Omega \times \beta$ and thus $\Pr(c(x) \geq \Omega) < \beta$ for desired $\beta \in (0,1]$.

[1]For validity of (1), d must be much larger than the wave length, which is about 5 cm for allocated DSRC channel [18]. In later analysis, e.g. (8) and (11), we conveniently use the notation that d can be integrated from 0^+ since this 5 cm is much smaller compared with the scale of a highway. Note that, (1) can also be extended to piece-wise linear model as in [15] and our methodology presented in this paper still holds for that case.

Now, let $V[u] \equiv E[(u - E[u])^2]$ denote the variance of a random variable u. Similar to (2), the variance of aggregated power level can be calculated by

$$V[c(x)] = \int_{-\infty}^{\infty} \rho(x+y)^2\lambda(x+y)^2 V[\omega(\tau(x+y),y)]dy. \quad (5)$$

Let $\Psi \equiv \phi^2 \times V[Z_1 Z_2]$, which can also be measured empirically as Φ. By plugging it in (5),

$$V[c(x)] = \Psi \times \int_{-\infty}^{\infty} \frac{\rho(x+y)^2\lambda(x+y)^2\tau(x+y)^2}{y^{2\gamma}} dy. \quad (6)$$

Given (6), if one wants to *probabilistically* control the aggregate power within a deviation threshold $\Delta > 0$ from $E[c(x)]$ for location x, by Chebyshev's inequality [1],

$$\Pr(|c(x) - E[c(x)]| \geq \Delta) \leq \frac{V[c(x)]}{\Delta^2}. \quad (7)$$

One can thus choose $\lambda(x)$ and $\tau(x)$ so that $V[c(x)] < \Delta^2 \times \alpha$ and thus $\Pr(c(x) \geq \Omega) < \alpha$ for desired $\alpha \in (0,1]$.

B. Uniform Vehicular Density with Uniform Transmission Rate-Power for Each Vehicle

If we assume uniform Tx probability and power, i.e. $\lambda(x) = \lambda$ and $\tau(x) = \tau$, $\forall x$, from (3) we get

$$E[c(x)] = \Phi\lambda\tau \times \int_{0^+}^{\infty} \frac{\rho(x+y) + \rho(x-y)}{y^\gamma} dy. \quad (8)$$

One simplest traffic scenario is that the density of vehicles on highway is uniform, i.e. $\rho(x) = \rho, \forall x$, then

$$E[c(x)] = 2\Phi\lambda\tau\rho \times \int_{0^+}^{\infty} y^{-\gamma} dy = \frac{2\Phi\lambda\tau\rho}{\gamma - 1}. \quad (9)$$

Given (9), if one wants to *probabilistically* control the aggregate power $c(x)$ under a certain threshold $\Omega > 0$, for any x,

$$\Pr(c(x) \geq \Omega) \leq \frac{E[c(x)]}{\Omega} = \frac{2\Phi\lambda\tau\rho}{(\gamma-1) \times \Omega}. \quad (10)$$

One can properly choose λ and τ so that $\lambda\tau < \frac{\beta(\gamma-1)}{2\Phi\rho} \times \Omega$ and thus $\Pr(c(x) \geq \Omega) < \beta$ for desired $\beta \in (0,1]$ for all x.

Similarly, from (6), the variance of the aggregated power level can be calculated for uniform Tx rate λ and power τ,

$$V[c(x)] = \Psi\lambda^2\tau^2 \times \int_{0^+}^{\infty} \frac{\rho(x+y)^2 + \rho(x-y)^2}{y^{2\gamma}} dy. \quad (11)$$

If vehicular density is uniform, i.e. $\rho(x) = \rho, \forall x$, then

$$V[c(x)] = 2\Psi\lambda^2\tau^2\rho^2 \times \int_{0^+}^{\infty} y^{-2\gamma} dy = \frac{2\Psi\lambda^2\tau^2\rho^2}{2\gamma - 1}. \quad (12)$$

Given (12), if one wants to *probabilistically* control the aggregate power $c(x)$ that deviates from $E[c(s)]$ within a threshold $\Delta > 0$, for any x,

$$\Pr(|c(x) - E[c(x)]| \geq \Delta) \leq \frac{V[c(x)]}{\Delta^2} = \frac{2\Psi\lambda^2\tau^2\rho^2}{(2\gamma-1) \times \Delta^2}. \quad (13)$$

One can thus choose λ and τ so that $\lambda^2\tau^2 < \frac{\alpha(2\gamma-1)}{2\Psi\rho^2} \times \Delta^2$ and thus $\Pr(|c(x) - E[c(x)]| \geq \Delta) < \alpha$ for desired $\alpha \in (0,1]$ for all x.

Besides, if one wants to control aggregated power so that $c(x)$ fulfills both the requirements in (10) and (13) w.r.t. parameters β and α, λ and τ needs to satisfy

$$\lambda\tau < \min(\frac{\beta(\gamma-1)}{2\Phi\rho} \times \Omega, (\frac{\alpha(2\gamma-1)}{2\Psi\rho^2})^{\frac{1}{2}} \times \Delta). \quad (14)$$

For uniform vehicular density, (14) tells us exactly how to choose uniform rate-power combination for desired DSRC channel quality.

C. Non-Uniform Vehicular Density with Uniform Transmission Rate-Power for Each Vehicle

In this subsection, we use a fluid model and conservation law to describe vehicular traffics. For non-uniform traffic density, LWR (Lighthill-Whitham-Richards) PDE (partial differential equation) [5], [6] relates vehicular density $\rho(x,t)$ and flow $q(x,t)$:

$$\frac{\partial\rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0. \quad (15)$$

With Greenshield's flux function [4], LWR PDE (15) can be written into a more commonly used form,

$$\frac{\partial\rho(x,t)}{\partial t} + v_f(1 - \frac{2\rho(x,t)}{\rho^*})\frac{\partial\rho(x,t)}{\partial x} = 0 \quad (16)$$

where ρ^* is the jam density and v_f is the free-flow velocity.

Solutions to (16) are shock (kinematic) waves, i.e. discontinuity of vehicular densities, moving with celerity $v_s(\rho_1, \rho_2)$, with ρ_1 and ρ_2 being density before/after that discontinuity,

$$v_s(\rho_1, \rho_2) = \frac{q(\rho_1) - q(\rho_2)}{\rho_1 - \rho_2} \quad (17)$$

which is referred as the Rankine-Hugoniot condition [3].

Shock waves include both compression waves and extension waves. A compression wave happens, for example, when a crash happens and vehicles gradually build up after that crash site. An extension wave, for example, happens when backlogged vehicles are released after a crash site is cleared. Note that, v_s in (17) is not the velocity of the flow; instead, this v_s represents how fast that density discontinuity moves. See more discussions in ch. 6 of [3].

For notational convenience in following derivation, let $\nu(x,y,t) \equiv \frac{\rho(x+y,t)+\rho(x-y,t)}{y^\gamma}$ and $\overline{c}(x,t) \equiv \frac{E[c(x,t)]}{\Phi\lambda\tau}$, then (8) can be rewritten as

$$\overline{c}(x,t) = \int_{0^+}^{\infty} \nu(x,y,t)dy. \quad (18)$$

By taking partial derivative of $\nu(x,y,t)$ w.r.t. t and x,

$$\frac{\partial\nu(x,y,t)}{\partial t} = \frac{1}{y^\gamma}(\frac{\partial\rho(x+y,t)}{\partial t} + \frac{\partial\rho(x-y,t)}{\partial t}) \quad (19)$$

and

$$\frac{\partial\nu(x,y,t)}{\partial x} = \frac{1}{y^\gamma}(\frac{\partial\rho(x+y,t)}{\partial x} + \frac{\partial\rho(x-y,t)}{\partial x}). \quad (20)$$

Combining (19) and (20), we get

$$\frac{\partial\nu(x,y,t)}{\partial t} + v_f(1 - \frac{2\rho(x,t)}{\rho^*})\frac{\partial\nu(x,y,t)}{\partial x} = 0 \quad (21)$$

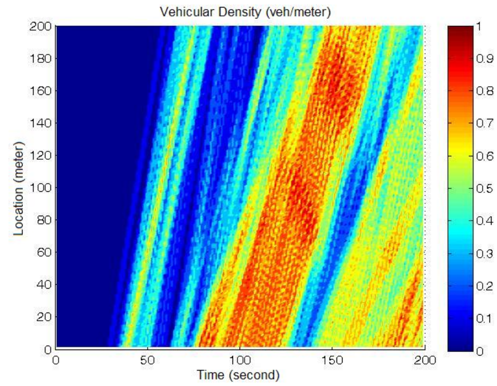

Fig. 1. An example of traffic density on a four-lane highway. Density is calculated by moving average (window = 10 meter). Traffic density propagates with time/space as indicated by the characteristics method in [3].

where ρ^* and v_f as defined the same as in (16). Now take partial derivative of $\overline{c}(x,t)$ w.r.t. t and x,

$$\frac{\partial\overline{c}(x,t)}{\partial t} = \int_{0^+}^{\infty} \frac{\partial\nu(x,y,t)}{\partial t}dy \quad (22)$$

and

$$\frac{\partial\overline{c}(x,t)}{\partial x} = \int_{0^+}^{\infty} \frac{\partial\nu(x,y,t)}{\partial x}dy. \quad (23)$$

Combining (21), (22), (23), we get

$$\frac{\partial\overline{c}(x,t)}{\partial t} + v_f(1 - \frac{2\rho(x,t)}{\rho^*})\frac{\partial\overline{c}(x,t)}{\partial x} = 0. \quad (24)$$

Following similar derivations from (18) to (24), let $\mu(x,y,t) \equiv \frac{\rho(x+y,t)^2+\rho(x-y,t)^2}{y^{2\gamma}}$ and $\widetilde{c}(x,t) \equiv \frac{V[c(x,t)]}{\Psi\lambda^2\tau^2}$, we get

$$\frac{\partial\widetilde{c}(x,t)}{\partial t} + v_f(1 - \frac{2\rho(x,t)}{\rho^*})\frac{\partial\widetilde{c}(x,t)}{\partial x} = 0. \quad (25)$$

These PDEs (24) and (25) are similar to the form of (16). Based on the technique of characteristics curves [3], we get

$$\frac{dx}{dt} = v_f(1 - \frac{2\rho(x,t)}{\rho^*}), \quad (26)$$

and thus the mean/variance of aggregated power $c(x,t)$ can be expressed as the propagation from a reference time t_0:

$$E[c(x,t)] = E[c(x - v_f(1 - \frac{2\rho(x,t)}{\rho^*})(t-t_0), t_0)], \quad (27)$$

and

$$V[c(x,t)] = V[c(x - v_f(1 - \frac{2\rho(x,t)}{\rho^*})(t-t_0), t_0)]. \quad (28)$$

Here we show one example of highway traffic and aggregated power level. SHIFT [21], a microscopic traffic simulator that models driver's behaviors, is used to produce vehicle trajectories. Fig. 1 show an example of vehicular density on a 200-meter segment of a single-direction, four-lane highway. This example shows an initially empty highway being gradually populated by incoming cars. One can clearly recognize characteristics curves and the propagation of density

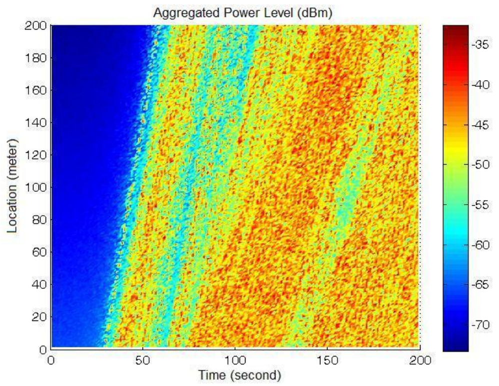

Fig. 2. One realization of the aggregated power level, with Tx probability λ = 0.5 and Tx power τ = 20 dBm, for the traffic in Fig. 1. Parameters for channel propagation model follows [15]. Note that shown aggregated power unit is in dBm, a log-scale measure.

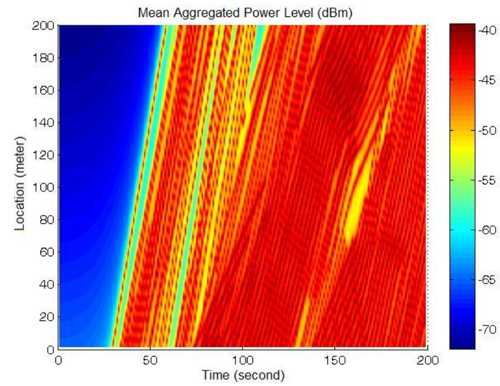

Fig. 3. Mean of aggregated power level for the same highway traffic in Fig. 1 with same parameters as in Fig. 2. As indicated by (27), this plot clearly illustrates characteristics curves and the density propagation over time/space in Fig. 1.

along with time/space. The same pattern can be seen in one realization of aggregated power level (Fig. 2) and more clearly in the mean of aggregated power (Fig. 3). Note that, shock waves (density discontinuity) appears in Fig. 1 and similar form of discontinuity can also be observed in Fig. 3.

In fact, the same can be shown for all cumulants of $c(x,t)$ (mean and variance are the first two cumulants) in the form of (27) and (28). With the one-to-one mapping property of a cumulant-generating function (logarithm of the moment-generating function) and a probability distribution [1], the probability distribution of $c(x,t)$, denoted as $f(c(x,t))$, can be expressed as propagation from a reference time t_0,

$$f(c(x,t)) =^d f(c(x - v_f(1 - \frac{2\rho(x,t)}{\rho^*})(t-t_0), t_0)). \quad (29)$$

Since the aggregated power level $c(x,t)$ propagates through time/space along with density, perceived interference and SIR of a given sender-receiver pair vary depending on the time/location. That is, some senders suffer extreme high BER (i.e. poor channel quality) while others do not. The uniform Tx rate-power suggested by VSCC report [19] might not be a good solution for status update messages in time-varying traffics. This observation justifies the need to use variable rate-power control discussed in next section.

III. Variable Transmission Rate-Power for Status Update Messages

In this section, we assume stationary rate-power control designs for all t and thus drop the notation t for $\lambda(x)$ and $\tau(x)$. We further argue that, for any sender-receiver pair at different location, they should perceive the same amount of interference (aggregated power level) due to status update messages. To this purpose, it is necessary to have $c(x,t)$ maintained constant for all location/time. In the same macroscopic understanding, an event-driven message, wherever it is initiated on the highway, can be protected if interference is kept at the same acceptable level at all location/time.

A. Upper Bound on Rate-Power Product

With a non-uniform vehicle density in (3) and (6), a practical (common) approach is to dynamically adjust Tx probability $\lambda(x) > 0$ and power $\tau(x) > 0$ so that $E[c(x,t)]$ and $V[c(x,t)]$ can be maintained constant for all location/time. This ensures that each sender, no matter it initiate a status update message or an event-driven message, perceives the same amount of interference from the shared channel.[2]

By inspecting (3) and (6), the only way to allocate Tx rate-power so that mean/variance of $c(x)$ stay constant for all location is to choose $\lambda(x)$ and $\tau(x)$ so that, $\forall x$,

$$\rho(x) \times \lambda(x) \times \tau(x) = B \quad (30)$$

where $B \in \mathbb{R}^+$ is a constant. With (30), for any location x,

$$E[c(x)] = \frac{2\Phi \times B}{\gamma - 1}, \quad (31)$$

and

$$V[c(x)] = \frac{2\Psi \times B^2}{2\gamma - 1}. \quad (32)$$

Note that, even by using the formula (30), the outcome of aggregated power level $c(x)$ is still a random process due to shadowing and multi-path effects; that is, due to Z_1 and Z_2 in (1).

First, that constant parameter B needs to be decided for (30). To *probabilistically* control the aggregate power under a threshold $\Omega > 0$, i.e.

$$\Pr(c(x) \geq \Omega) \leq \frac{E[c(x)]}{\Omega} = \frac{2\Phi \times B}{(\gamma-1) \times \Omega}, \quad (33)$$

and deviation bound $\Delta > 0$ from its mean $E[c(x,t)]$, i.e.

$$\Pr(|c(x) - E[c(x)]| \geq \Delta) \leq \frac{V[c(x)]}{\Delta^2} = \frac{2\Psi \times B^2}{(2\gamma-1) \times \Delta^2}, \quad (34)$$

[2]This sense of *fairness* is similar to the water-filling idea in [10]. Nevertheless, we work on the aggregated power instead of aggregated data rate (as in [10]). The reason is that, unless using centralized scheduling, data rate is not a physical measure that can be added together while perceived power level can be calculated by superposition as done in this paper.

one can properly design $\lambda(x)$ and $\tau(x)$, i.e. $\lambda(x) \times \tau(x) = B \times \rho(x)^{-1}$, to bound $\Pr(c(x) \geq \Omega) < \beta$ and $\Pr(|c(x) - E[c(x)]| \geq \Delta) < \alpha$ for desired $\beta, \alpha \in (0, 1]$ for all x. With (33) and (34) together, the constant B needs to satisfy

$$B < \min(\frac{\beta(\gamma-1)}{2\Phi} \times \Omega, (\frac{\alpha(2\gamma-1)}{2\Psi})^{\frac{1}{2}} \times \Delta). \qquad (35)$$

Consequently, to maintain desired DSRC channel quality, rate-power product must satisfy this bound:

$$\lambda(x) \times \tau(x) < \frac{\min(\frac{\beta(\gamma-1)}{2\Phi} \times \Omega, (\frac{\alpha(2\gamma-1)}{2\Psi})^{\frac{1}{2}} \times \Delta)}{\rho(x)}. \qquad (36)$$

Since Tx bit rate is proportional to $\lambda(x)$ and targeted Tx range is proportional to $\tau(x)$, (36) tells us that the total broadcast information amount per unit time must also be bounded by a product form of bit-rate and targeted range.[3] This bound (36) matches with the wireless capacity notion (bit-meter per second) of a wireless ad-hoc network from [7].

B. Different Rate-Power Control Ideas

Given density $\rho(x)$ at that location x, one has the freedom to choose Tx rate $\lambda(x)$ and power $\tau(x)$ as long as

$$\lambda(x) \times \tau(x) = B \times \rho(x)^{-1}. \qquad (37)$$

To satisfy (37), there are many potential rate-power control designs to decompose this product form. Some of them are discussed below. Note that, $A, D \in \mathbb{R}^+$ and $B = A \times D$ in below description.

(D.1): $\lambda(x) = A$ and $\tau(x) = D \times \rho(x)^{-1}$. In this design, a vehicle transmits self-state information with the same rate but with a smaller Tx power when the network density is high. This kind of broadcasting policy uses the same state information intensity (rate) but adapts its Tx power to change the number of intented broadcast receivers and reduce interference to each other.

(D.2): $\lambda(x) = A \times \rho(x)^{-1}$ and $\tau(x) = D$. In this design, a vehicle transmits self-state information with less rate when the network density is high. This kind of broadcasting policy uses a fixed Tx power to reach a targeted distance while adapting Tx rate so that interference in the channel is maintained in a constant level for all location.

(D.3): $\lambda(x) = A \times v(x)$, i.e. a vehicle broadcasts with higher information rate when it is traveling with a higher speed, and $\tau(x) = D \times v(x)^{-1}\rho(x)^{-1} = D \times q(x)^{-1}$. The idea behind this design is that, when a vehicle travels with higher velocity, its position and status might change more radically, thus higher Tx probability (and more state information) is required for neighboring cars to perform stable tracking.

(D.4): $\lambda(x) = A \times |v'(x)|$, i.e. a vehicle broadcasts with higher probability when it accelerates or decelerates (changes of dynamics), and $\tau(x) = D \times |v'(x)|^{-1}\rho(x)^{-1}$. In this design, a vehicle uses its acceleration/deceleration and detected traffic density $\rho(x)$ to jointly decide its Tx rate and power.

[3] One may define minimum required SIR so that information can be decoded correctly as the *physical model* in [7] and derive this bound in a similar way.

Among those ideas, density-based power allocation like **(D.1)** can be found in [10], [13]. **(D.2)** works for safety applications that require specific range to reach. Similar to [14], [22], **(D.3)** and **(D.4)** include vehicle dynamics into rate-power control.

C. Proposed Rate-Power Control

In this subsection, we propose a rate-power control algorithm that decides rate and power for status update messages. Different from designs in [14], [22], we seek a decentralized algorithm that uses traffic engineering intuition so that each vehicle can simply decide its rate-power pair based on its own current state.

Our algorithm is proposed based on two observations from vehicle safety perspectives. First, the dynamics of a nearby vehicle is more involved with a subject vehicle and it might be more dangerous if a subject vehicle does not know the movements of its immediate neighbors. Secondly, this involvement of dynamics gradually decreases as distance increases; that is, movements of far-away vehicles are less important to a subject vehicle. Therefore, for this VANET tracking problem, we choose to decide rate first so that enough information rate is provided to nearby vehicles and then, based on the form of (37), the Tx power is decided.

Here, we propose a practical rate-power control for status update messages, which closely resembles **(D.3)** design. Let $j \in \mathbb{N}$ denote the index of vehicle and $v_j(t)$ be the velocity of that particular vehicle at time t. For this vehicle, its Tx probability $\lambda_j(t)$ is decided by its own velocity (as the approximation of average speed of that traffic flow):

$$\lambda_j(t) = A \times v_j(t). \qquad (38)$$

Based on Greenshield's flux function [4], Tx power $\tau_j(t)$ for this vehicle is also decided by its own velocity $v_j(t)$:

$$\tau_j(t) = \min(D \times (v_j(t) \times \rho^* - \frac{\rho^*}{v_f} v_j(t)^2)^{-1}, 1) \qquad (39)$$

and thus $\tau_j(t) \in (0, 1]$ Watt (following FCC regulation [18]). In this design, a vehicle uses its own speed as input to control Tx rate-power pair. We choose $A = v_f^{-1}$ so that a vehicle broadcasts with probability 1 when it's traveling with free flow speed. We choose $D = 0.1 \times \frac{\rho^* v_f}{4}$ so that a vehicle broadcasts with *at least* 100 mW (20 dBm) when the traffic flow is maximized. Therefore, $B = A \times D = \frac{\rho^*}{40}$ in (37).

D. Tracking Performance in OPNET Simulations

In this subsection, we put the rate-power control designs on top of the 802.11 protocol stack and compare tracking performance between proposed algorithm and the "beaconing with uniform rate-power" method [19]. Since variable rate-power control can reduce interference and help vehicles share the channel, we expect its tracking performance to be further improved from that of a uniform rate-power design.

In OPNET [20], we use modified 802.11a PHY module working at 5.9 GHz with 10 MHz bandwidth. We follow the DSRC channel model reported in [15], where path loss

TABLE I

COMPARISON OF UNIFORM AND VARIABLE RATE-POWER DESIGNS

90% Threshold of Euclidean Tracking Error (meter)				
Design	congested (14 mph)	low speed (30 mph)	medium speed (53 mph)	free flow (74 mph)
Uniform	1.60 m	1.22 m	1.02 m	0.82 m
Variable	1.32 m	1.07 m	0.89 m	0.71 m

99% Threshold of Euclidean Tracking Error (meter)				
Design	congested (14 mph)	low speed (30 mph)	medium speed (53 mph)	free flow (74 mph)
Uniform	3.78 m	2.42 m	1.56 m	1.09 m
Variable	2.13 m	1.73 m	1.01 m	0.87 m

exponent γ = 2.31, and simplify far distances as Rayleigh fading (instead of pre-Rayleigh). The DSRC transceiver operates with 3 Mbps raw rate, -87 dBm Rx sensitivity. The payload size of each information exchange is 300 bytes. IEEE 802.11 CSMA/CA mechanism is not modified. Vehicle trajectories are produced by SHIFT [21]. Total simulation duration is 30 seconds for a four-lane, single-direction, 1-Km highway. We use a mean gap of 0.8 second between vehicles. Four traffic scenarios are simulated and listed in Table I.

During the simulation, every 50-msec, each vehicle gets a measurement of its own status (position, speed, heading) from sensors, and the on-board measurement noise is modeled based on experiment data [12]. A subject vehicle uses its own speed as input to decide its rate-power pair by (38) and (39), with v_f = 40 meter/sec and ρ^* = 0.8 vehicle/meter. A packet will be generated as the result of Bernoulli trial with probability $\lambda_j(t)$ and then placed in MAC queue. The associated Tx power $\tau_j(t)$ will be attached in the packet and used by PHY layer to transmit this packet. This mechanism basically follows the design of WSM (WAVE Short Message) in IEEE 1609.3 [17]. For the uniform rate-power case (i.e. beaconing), we use λ = 0.5 and τ = 100 mW (20 dBm) for all vehicles at all time.

Each vehicle has a bank of estimators that track all neighboring vehicles. Upon receiving information from a particular car, each vehicle updates its estimate toward that car based on a constant speed predictor, in which a car is assumed to run with the same speed/heading after each status update. The proximity of a vehicle is defined as the area of 150-meter radius to satisfy most safety applications identified in [19].

After each simulation run, statistics are collected from neighbors within this proximity of a subject vehicle. We calculate tracking error based on the Euclidean norm of true position of that vehicle and estimated positions produced by all its neighbors. Based on this error calculation across all vehicles and all epochs, 90% threshold and 99% threshold of Euclidean tracking error are provided in Table I. These two thresholds measure the accuracy of a rate-power control algorithm as in [22]. For example, 90% threshold means that, of all tracking errors from all epochs in simulation, 90% of Euclidean tracking error is below this number. Similarly, 99% threshold tells us that, only 1% of error (during simulation) is larger than this number and this gives us statistically how large the tracking error could be.

The results in Table I show that, with variable rate-power control, tracking error is reduced from that of beaconing, especially in congested traffic scenario. With 99% threshold, the performance difference is more dramatic. Although our macroscopic model suffers the same weaknesses of all other macroscopic ones, e.g. loss of optimality due to approximating vehicle traffics by a fluid model, it gives us the right intuition on how to design rate-power control.

IV. CONCLUDING REMARKS

In this paper, we study the rate-power control for status update messages in VANETs. We first analyze the aggregated power level resulted from uniform rate-power design using a macroscopic model. Guidelines to design variable rate-power control are provided based on intuitions from traffic engineering. Simulation results indicate that, compared with beaconing, our proposed rate-power control can lower interference in DSRC channel and thus enhance tracking performance.

REFERENCES

[1] R. Durrett, *Probability: Theory and Examples*, Duxbury Press, 2004.

[2] P. Santi, Topology Control in Wireless Ad Hoc and Sensor Networks, John Wiley and Sons, 2005.

[3] A. M. Bayen, CE 291F lecture notes, U. C. Berkeley, Spring 2009.

[4] B. D. Greenshield, "A study of traffic capacity," *Proc. of Highway Research Board*, 14: pp. 448-477, 1935.

[5] M. J. Lighthill, G. B. Whitham, "On kinematic waves. II. A theory of traffic flow on long crowded roads," *Proc. of the Roy. Soc. of London*, pp. 317-345, 1956.

[6] P. I. Richards "Shock waves on the highway," *Operation Research*, 4(1): pp. 42-51, 1956.

[7] P. Gupta, P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Info. Theory*, vol.46, No.2, Mar. 2000.

[8] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE JSAC*, vol.18, No.3, Mar. 2000.

[9] T. K. Mak, K. Laberteaux, R. Sengupta, "A Multi-channel VANET Providing Concurrent Safety and Commercial Services," *Proc. of 2nd ACM VANET*, Sept. 2005.

[10] J. Mittag, F. Schmidt-Eisenlohr, M. Killat, J. Harri, H. Hartenstein, "Analysis and Design of Effective and Low-overhead Transmission Power Control for VANETs," *Proc. of 5th ACM VANET*, Sept. 2008.

[11] C. Robinson, L. Caminiti, D. Caveney, K. Laberteaux, "Efficient Coordination and Transmission of Data for Vehicular Safety Applications," *Proc. of 3rd ACM VANET*, Sept. 2006.

[12] R. Sengupta *et al.*, "Cooperative Collision Warning Systems: Concept Definition and Experimental Implementation," *Jour. of Intell. Transport. Systems*, vol.11, No.3, pp. 143-155, 2007.

[13] M. Artimy, W. Robertson, W. Philips, "Assignment of Dynamic Transmission Range Based on Estimation of Vehicle Density," *Proc. of 2nd ACM VANET*, Sept. 2005.

[14] S. Rezaei, R. Sengupta, H. Krishnan, X. Guan, "Reducing the Communication Required by DSRC-based Vehicle Safety Systems," *Proc. of 4th ACM VANET*, Sept. 2007.

[15] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, P. Mudalige, "Mobile Vehicle-to-Vehicle Narrow-Band Channel Measurement and Characterization of the 5.9 GHz Dedicated Short Range Communication Frequency Band," *IEEE JSAC*, vol.25, no.8, Oct. 2007.

[16] Wireless Access in Vehicular Environment (WAVE) in standard 802.11, specific requirements: IEEE 802.11p/D1.0, Feb. 2006.

[17] IEEE 1609.3 and 1609.4 for Wireless Access in Vehicular Environment: Networking Services and Multi-channel Operations, 2007.

[18] FCC's channel allocation for DSRC, see http://www.fcc.gov.

[19] Vehicle Safety Communications Consortium (VSCC), "Vehicle Safety Communication Project Final Report," 2005.

[20] OPNET Modeler 14.0, http://www.opnet.com/.

[21] California PATH SHIFT, http://path.berkeley.edu/SHIFT/.

[22] C. L. Huang *et al.*, "Robustness Evaluation of Decentralized Self-Information Dissemination Control Algorithms for VANET Tracking Applications," *accepted by VTC-fall 2009*, to appear.