Effect of Transmission Parameters on Efficiency and Reliability of V2V Networks

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ABSTRACT

Vehicle-to-vehicle communications is essential to create cooperative awareness amongst vehicles, improve roadway safety and roadway capacity, and reduce green house gas emissions. As vehicle density increases, the amount of cooperative awareness messages also increases, which in turns increases the amount of background interference in the wireless channel. Transmission under high degree of background interference reduces the reliability of the packet. Adjusting transmission parameters such as transmission power or backoff mechanism may reduce interference, but they also decrease efficiency of packet transmission. This paper quantifies the tradeoff between transmission efficiency and reliability, and shows how various transmission parameters affect overall system performance.

INTRODUCTION

Vehicular networking [1]-[5] is the key technology that will improve safety for road users and efficiency of transportation systems. Over the past few years, EU programs such as CVIS [6], SAFESPOT [7] and COOPERS [8] have demonstrated the importance of cooperative awareness in vehicle networks. Through driving simulator, it has been reported that appropriate in-vehicle warnings can prompt drivers to reduce vehicles speed by 10%, and deviating only 5% of vehicles on a critical road segment is sufficient to keep traffic fluent and save energy [8]. The overall European ITS communication architecture has been published by COMeSafety. The C2C Communication Consortium [9] has been working closely with ETSI to create an open European industry standard [10] for V2V communications. Multiple ISO standards are created for Communications Access for Land Mobiles (CALM) [11] that specifies the architecture, management, networking, and air interface of vehicle networks. In particular, the M5 air interface in ISO-21218 is based on the IEEE 802.11p [12] and Wireless Access in Vehicle Environment (WAVE) P1609 [13] protocols.

To enable cooperative awareness, vehicles periodically send Cooperative Awareness Messages (CAMs) containing their positions, speeds, headings, accelerations and control status such as brake, steering angle, throttle position and exterior lights. Nearby vehicles that hear these messages may use them to reconstruct a local dynamic map of its surrounding, and generate alert messages as necessary to warn drivers of impending danger. From a system architecture point of view, it is important to know the following performance metrics: (1) the amount of data that a vehicle can deliver to its neighbors in a given time, (2) the number of nearby vehicles that receive a specific transmitted packet successfully, and (3) the expected distance that a message travels in a single transmission. If a packet is transmitted in isolation, these metrics can be simultaneously optimized by increasing the packet transmission power. However, due to the decentralized nature of V2V networks, an increase in transmission power also increases the amount of background interference. In fact, there is often a tradeoff between the various performance metrics depending on the overall strategy for communications.

Figure 1 illustrates how various protocol parameters affect the broadcast efficiency and reliability of a vehicular network. In Figure 1a, due to limited transmission power, only vehicle B receives the packet transmitted by vehicle A successfully; vehicles C, D and E cannot receive the packet. In Figure 1b, when the transmission from vehicle A uses either a higher transmission power or a lower modulation format (hence, lower transmission rate), more vehicles (B, C and D) can decode the packet successfully. If packets are transmitted in isolations, it is possible to increase both broadcast efficiency and reliability by increasing transmit power of each packet transmission. However, as shown Figure 1c, when vehicles A and E transmit packets simultaneously, vehicles C and D can neither decode the packets from vehicle A nor that from vehicle E due to the interference. Here, competition from various nodes reduces reliability of transmission. A communication protocol needs to adjust the probability that such simultaneous transmission event occurs. Specifically, reducing the probability of packet transmission at a given time will allow each transmitted packet to reach more nearby nodes (like in Figure 1b), but this also implies that each node needs to sacrifice its overall data transmission rate, which reduces the efficiency of the communication protocol. Finally, as vehicle density increases, the overall communication resource is shared amongst more vehicles, thus each vehicle must reduce its transmission probability, and the coverage of a given transmission may become smaller due to increased background interference level. However, due to increased density, the total number of vehicles that receive a specific transmission may be larger.

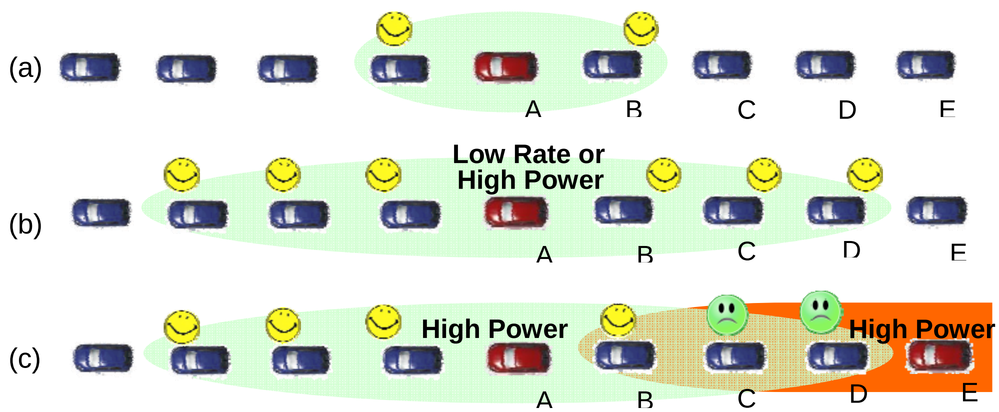

Figure 1 Efficiency and reliability of packet transmission due to interference.

In this paper, we analyze the broadcast efficiency and reliability of a vehicular network, and examine how various communication parameters lead to tradeoff between these metrics. For broadcast efficiency, we consider the average data rate received by a node in both packets/sec and bits/sec. For broadcast reliability, we consider the average number of nodes that successfully receive a packet, and the average distance to which a packet is delivered. We show: (1) the performance of transmission from emergency vehicles who use higher transmission power; (2) the effect of vehicle density on efficiency and reliability; and (3) the tradeoff of efficiency and reliability as transmit power, transmission probability, and modulation scheme vary.

KEY ANALYTICAL RESULTS

We consider a vehicular network consisting of a number of packet generating nodes (vehicles) that broadcast information to their neighbors. We assume that the nodes always have packets waiting in their outgoing queues, and all packets have the same size of L bits. We perceive that the nodes are present in a stretch of straight highway, and we omit lane information for simplicity. Hence, nodes are aligned in a one-dimensional linear space, modeled by a one-dimensional (1-D) homogeneous Poisson point process with mean λ.

The system has a single broadcast channel that is shared amongst all nodes. Before sending a packet, the node first senses whether the channel is free. If it is so, the node broadcasts a packet with probability c regardless of the actions of the other nodes in the system. When a node transmits a packet, it transmits the packet without interruption for T_{tx} seconds. If the node chooses to not transmit when a channel is free, it waits for T_{slot} seconds before it senses the channel again. Finally, if the channel is not free, the node attempts to decode the packet, and senses the channel again afterwards. This procedure is very similar to the *p*-persistent Carrier-Sense Multiple Access (CSMA) [14].

We assume that the wireless channels exhibit Rayleigh fading characteristics, and the path loss exponent is α. The receiver has only single packet reception capability. For a given modulation and coding scheme, the packet received with power s can be decoded successfully if and only if its received SINR exceeds a modulation dependent threshold z (z>1).

PROBABILITY OF PACKET RECEPTION

To understand the impact of interference in V2V networks, we first analyze the probability that a node receives a specific (i.e. emergency) packet of transmission power p_1 successfully when the source of the packet is d meters away, while other nodes transmit interfering packets with probability c at a transmission power p_0.

Lemma 1: Consider a 1-D wireless network with mean λ. Each node independently transmits an interfering packet with probability c. Then, the probability of successfully receiving the specific packet when the receiving node is distance d away from the source is

$$P(\mathrm{succ} \mid d) = \int_0^\infty P(\mathrm{succ} \mid s)\, g(s \mid d)\, \mathrm{d}s\,, \tag{1}$$

where $P(\mathrm{succ}|s)$ is the probability of successfully decoding a packet with received power s,

$$P(\mathrm{succ} \mid s) = \exp\left(-2\lambda c \int_0^\infty \exp\left(-p_0^{-1} x^{\alpha} \left(z^{-1} s - n_0\right)\right) \mathrm{d}x\right),\ \forall s \ge z n_0\,, \tag{2}$$

And $g(s|d)$ is the distribution of the received power from the source that is distance d away under Rayleigh fading,

$$g(s \mid d) = \frac{1}{p_1 d^{-\alpha}} \exp\left(-\frac{s}{p_1 d^{-\alpha}}\right),\ \forall s \ge 0\,. \tag{3}$$

Proof: The derivation of (2) is submitted to [15], and is omitted here for brevity. Eq. (1) directly follows from the total probability formula. ■

In Figure 2, we show the reception probability at a fixed distance (left) as well as the reception probability as a function of distance away from the specific source (right). We note that an increase in the transmit power of a specific packet can improve its reception probability if all other nodes maintain a fixed power. However, as shown in left-side figure, quadrupling transmission power only improves reception probability of a node at 10 meters away by less than 5%. Figure 2 is important for understanding the dissemination of high priority information from emergency vehicles. For example, in IEEE 802.11p, emergency vehicles are allowed to broadcast emergency message at 43dBm, while all other vehicles have a transmission power limit of 33dBm. Note that, even at increased transmission power, the transmission range is limited.

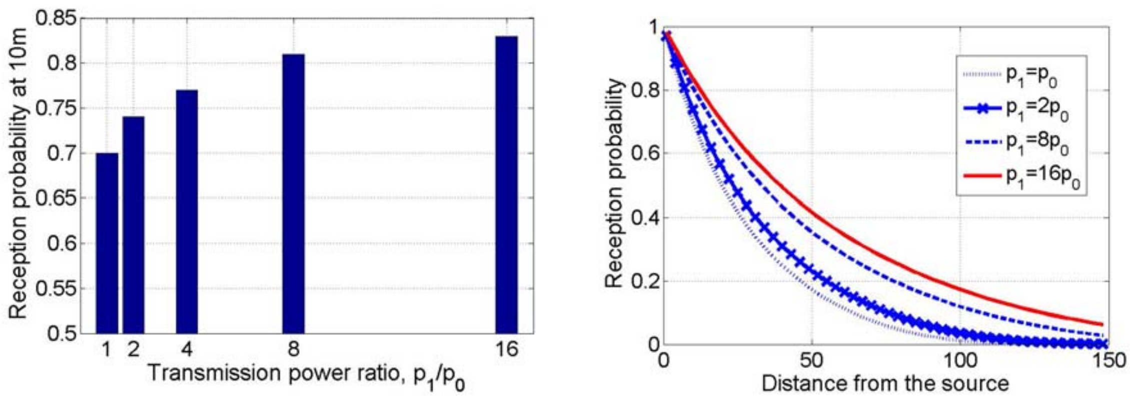

Figure 2 (left) Reception probability of a specific source at 10 m, and (right) Reception probability as a function of distance. The transmit power of background traffic is p_0 = 27dBm, the transmit power of the specific source is p_1, c=0.05, λ=0.25 veh/m, BPSK.

BROADCAST RELIABILITY

We consider two metrics that measure the reliability of a packet transmission: (1) the expected distance away from the source at which vehicles successfully decode a packet, and (2) the expected number of vehicles that receive a broadcast successfully.

Theorem 1: The expected distance of vehicles receiving a packet successfully is

$$D = \frac{\int_0^\infty xP(\text{succ} \mid x)\,dx}{\int_0^\infty P(\text{succ} \mid x)\,dx}, \tag{4}$$

and the expected number of vehicles that decode a packet successfully is

$$E[N] = \frac{1-c}{cz^{1/\alpha}}\left(\frac{p_1}{p_0}\right)^{1/\alpha}\left(1-\exp\left(-2\lambda c\left(\frac{p_0}{n_0}\right)^{1/\alpha}\Gamma\left(1+\frac{1}{\alpha}\right)\right)\right), \tag{5}$$

where Γ(.) is the Gamma function.

Proof: It is easy to see that

$$
\begin{aligned}
D &= E\left[\text{distance} \mid \text{successful reception}\right] \\
&= \frac{E\left[\text{Reception location }\right]}{\Pr[\text{Successful reception}]} \\
&= \lim_{M\to\infty} \frac{\int_0^M \frac{1}{M}\, xP\left(succ \mid x\right)dx}{\int_0^M \frac{1}{M}\, P\left(succ \mid x\right)dx},
\end{aligned}
$$

where $P(succ|x)$ is given by Lemma 1. The proof of (5) is submitted to [15], and is omitted in this paper for brevity. ■

Figure 3 shows the broadcast reliability as a function of vehicle density. On the left, we see that, with all communication parameters fixed, the expected distance of a transmitted packet decreases as the density increases. This is due to the increased number of transmission – thus interference – in a given area. Higher vehicle density lowers the SINR of received packet at every receiver location, and thus decreases the range of transmission. Ironically, on the right-side figure, we see that the expected number of receiving vehicles increases monotonically as the density increases. This is because there are more neighbors (potential receivers) surrounding the source vehicle. During traffic jam (i.e., node density is high), the expected number of vehicles that decodes a packet successfully remains about the same regardless of the actual density. This fact is significant for network protocol design, as the number of next hop neighbor is constant during traffic jam.

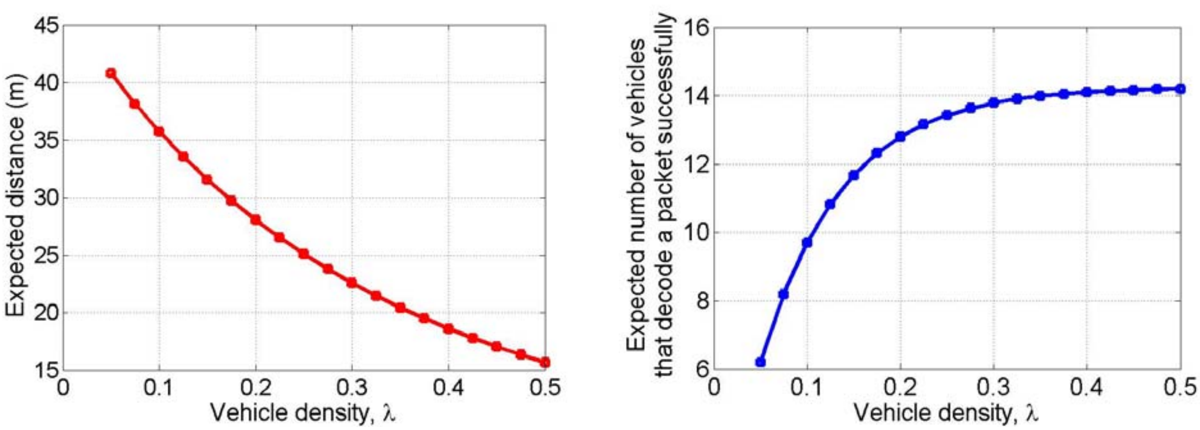

Figure 3 Broadcast reliability as a function of vehicle density: (left) the expected distance of a vehicle receiving a packet successfully and (right) the expected number of vehicles that decode a packet successfully. Transmit power p_1=p_0=27 dBm, c=0.05, BPSK.

BROADCAST EFFICIENCY

We use the expected number of packets and bits that a vehicle successfully receives in unit duration to measure the broadcast efficiency. Here, we assume that every node transmits packets at the same power p_0, and the time at which the nodes in the network perform carrier sensing is synchronized, we have the following result:

Theorem 2: The broadcast efficiency in packets per second of a 1-D broadcast wireless network is

$$U(c,\lambda,p_0,L)=\frac{(1-c)z^{-1/\alpha}\left(1-\exp\left(-2\lambda c(p_0/n_0)^{1/\alpha}\Gamma(1+1/\alpha)\right)\right)}{T_{tx}-(T_{tx}-T_{slot})(1-c)^{2\lambda(p_0/p_{cs})^{1/\alpha}}} \quad \text{(pkts/sec)}, \qquad (6)$$

and the expected data rate in bits per second that a node receives any packets successfully is

$$R_{\text{recv}}=U(c,\lambda,p_0,L)L \quad \text{(bits/sec)},$$

where L is the fixed payload size in bits, T_{slot} is the slot duration defined in IEEE 802.11p, T_{tx} is the duration needed to transmit a packet, and p_{cs} is the physical carrier sense threshold.

Proof: The detail proof for (6) is submitted to [15], and is omitted in this paper for brevity. ■

Figure 4 shows the broadcast efficiency as a function of vehicle density. We see that, as functions of density, both efficiency metrics follow a similar pattern when the packet size is fixed. We will explore details about the relationship between efficiency and reliability under various protocol parameters in the next section.

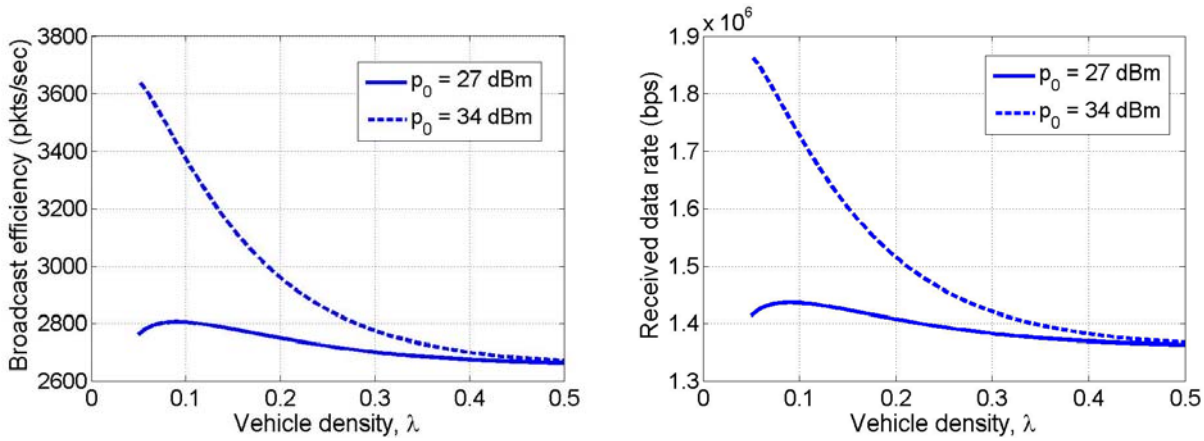

Figure 4 Broadcast efficiency vs. vehicle density: (left) the expected number of packets that a node can receive in unit time, and (right) received data rate. *c*=0.05, *L*=512 bits, BPSK.

EFFECT OF VARYING PROTOCOL PARAMETERS

In this section, we fix the vehicle density to one of these three scenarios: rural (λ=0.1 veh/m), city (λ=0.25 veh/m) and traffic jam (λ=0.5 veh/m). We examine how various protocol parameters affect broadcast efficiency and reliability. In this section, we assume that each vehicle broadcasts fixed length packet using identical transmit power.

TRANSMISSION POWER

In Figure 5, we show the tradeoff of broadcast efficiency and reliability as the transmit power p_0 changes from 0 dBm to 37 dBm. In Figure 5, the left-most point of each line segment corresponds to the lowest transmit power. As transmit power increases, both the expected number of vehicles that decodes a packet successfully (left x-axis) and the expected distance (right x-axis) increases. In rural and city scenarios, increasing power first has positive effect on broadcast efficiency; however, further increase in transmit power reduces the efficiency. This suggests that a power control strategy is important for low to medium density scenarios. Finally, in traffic jam (extremely dense) scenario, increasing power only decreases broadcast efficiency, even though the transmission reliability improves as power increases. Hence, any protocol would need to tradeoff the amount of data a node in the network can receive in unit time, and the amount of nodes that can receive a specific transmission.

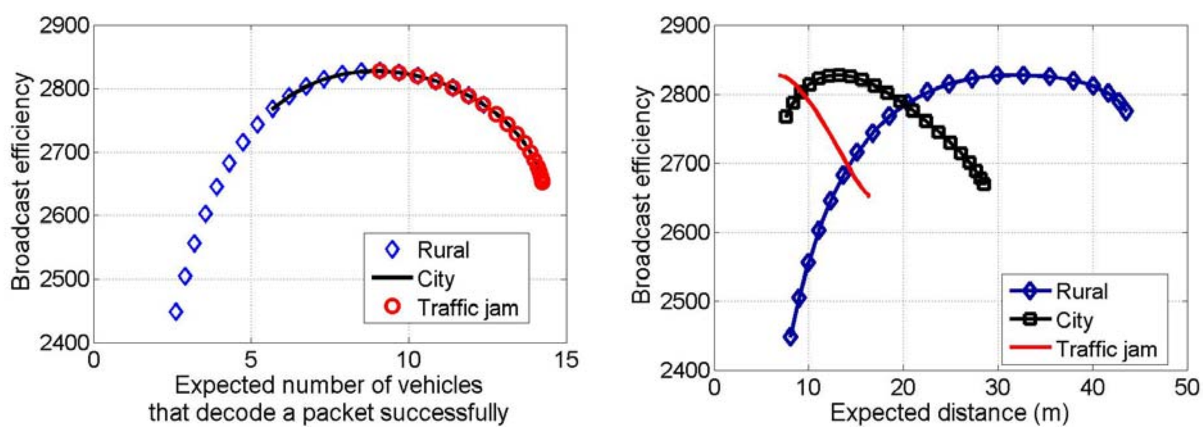

Figure 5 Tradeoff of broadcast efficiency and reliability due to transmission power: (left) broadcast efficiency vs. the expected number of vehicles that decode a packet successfully, and (right) broadcast efficiency vs. the expected distance. *c*=0.05, *L*=512, BPSK.

Another observation we can make is that when all vehicles are broadcasting using the same power, and all other transmission parameters are fixed, the same efficiency and reliability (expected number of receivers) can be obtained when we set

$$p_0^{1/\alpha} \propto \frac{1}{\lambda},$$

where $\propto$ signifies proportionality. This result can be readily seen by the fact that $\lambda p_0^{1/\alpha}$ always appears together in (5) and (6), and is verified by Figure 5 (left).

TRANSMISSION PROBABILITY

Figure 6 shows the tradeoff of efficiency and reliability as the transmission probability *c* varies. As *c* increases, each node has higher probability of transmitting a packet, which increases the background interference. Hence, the maximum reliability is reached when *c* is close to zero (point A in the left-side figure, point D in the right-side figure). However, this comes at the expense of broadcast efficiency, as almost all nodes refrain from transmitting. As *c* increases, the broadcast efficiency first increases due to an increase in transmission rate; but it eventually decrease again due to excessive interference. The optimal broadcast efficiency is characterized fully in [3] and [15]. The broadcast reliability decreases monotonically as *c* - hence the interference level - increases. As one can see from the left-side figure, the maximum efficiencies of three scenarios are very close. However, the expected number of receivers depends considerably on density. When reliability is measured in terms of the expected distance as in the right-side figure, one can carefully tune parameter *c* in different scenarios to approach a same point (point E) on the efficiency-reliability plane. Any internal point can be achieved through time-sharing strategy. For *p*-persistent CSMA protocol, a system should operates on the line segment connecting points A and B.

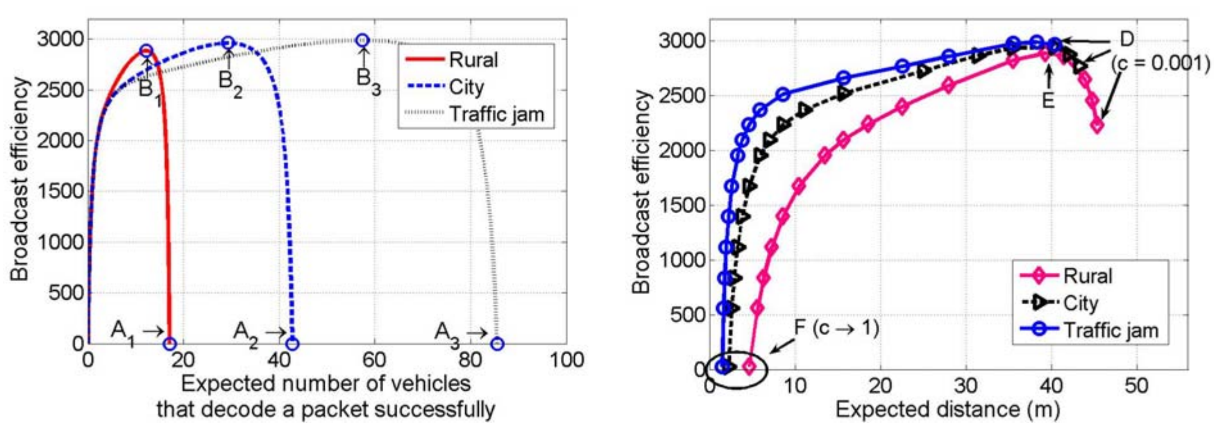

Figure 6 Tradeoff of broadcast efficiency and reliability due to transmission probability: (left) broadcast efficiency vs. expected number of vehicles that decode a packet successfully, and (right) broadcast efficiency vs. expected distance. p_0=27 dBm, *L*=512 bits, BPSK.

MODULATION SCHEME

Figure 7 shows the inter-relationship between efficiency and reliability as modulation scheme varies. Different modulations in IEEE 802.11p offer different data rates, however, the SINRs required to successfully decode a packet in different modulation are also different. Higher data rate comes at the cost of higher SINR requirement. In **Table 1**, we summarize various aspects of the four modulations we used in this subsection. In the full buffer model, each node always has packets waiting in its outgoing queue. The packet length is fixed, so that the transmission time of a packet is inversely proportional to its data rate. In Figure 7, we observe that lower data rate is more reliable. However, optimal efficiency is achieved when transmission rate is set at 6Mbps (QPSK). A similar observation was also made in simulation results in [16], which suggests that QPSK is the best data rate selection in most v2v communication scenarios.

Modulation	**Coded bits per sub-carrier**	**Coded bits per OFDM symbol**	**Coding rate**	**Data bits per OFDM symbol**	**Data rate for 10MHz channel**	**Capture threshold**
BPSK	1	48	1/2	24	3 Mbps	5 dB
QPSK	2	96	1/2	48	6 Mbps	8 dB
QAM-16	4	192	1/2	96	12 Mbps	15 dB
QAM-64	6	288	2/3	192	24 Mbps	25 dB

Table 1 IEEE 802.11p Modulations

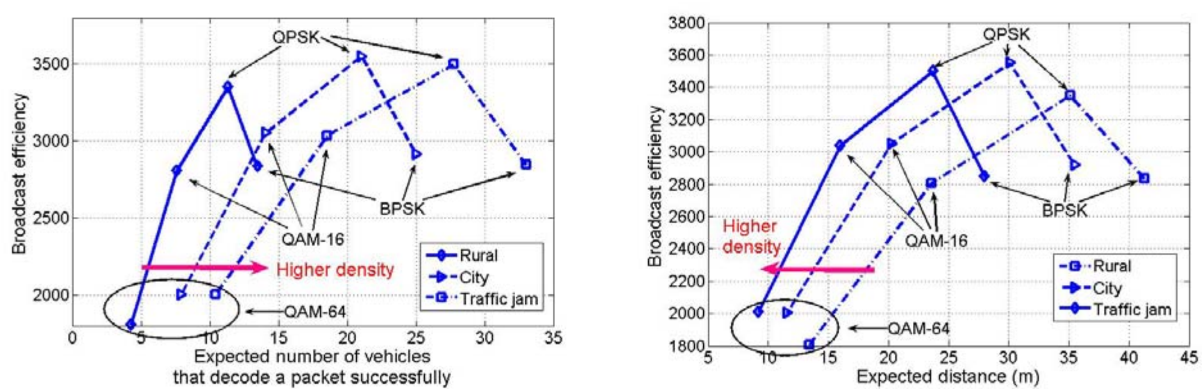

Figure 7 Tradeoff of broadcast efficiency and reliability due to modulation scheme. *c*=0.05, p_0=27 dBm, *L*=512 bits.

We summarize the effect of the various parameter changes to the system efficiency and reliability below in **Table 2**.

Increasing System Parameters	Broadcast Efficiency	Broadcast Reliability	
		Number of receiving nodes per transmission	Expected transmission distance
Density λ	Increase first, then decrease	Increase	Decrease
Transmission Power p_0	Increase first, then decrease	Increase	Increase
Transmission Probability *c*	Increase first, then decrease	Decrease	Decrease
Modulation Symbol size	Increase first, then decrease	Decrease	Decrease

Table 2 Summary of the effect of systems parameters to efficiency and reliability

CONCLUSIONS

Broadcasting cooperative awareness messages by all vehicles is the basis for various safety and non-safety related applications in vehicular networks. Pursuant to one of the first investigations of its kind, we examine the effect of the various transmission parameter changes to the broadcast efficiency and reliability of such messages in presence of background interference. We show the following fundamental results: (1) the quantified effects of raising transmit power for one specific emergency packet; (2) with all other parameters fixed, as density increases, the expected number of vehicles that receives a specific packet increases; however, the expected distance of a receiving vehicle decreases; (3) the tradeoff of efficiency and reliability as transmit power, transmission probability and modulation scheme vary separately. These investigations provide guidelines for vehicular network system optimization.

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