# Impact of Beaconing Policies on Traffic Density Estimation Accuracy in Traffic Information Systems

Saeed Bastani* Lavy Libman*,‡ S. Travis Waller†,‡
* School of Computer Science and Engineering, University of New South Wales, Sydney, NSW 2052, Australia
† School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia
‡ National ICT Australia, 13 Garden St, Eveleigh, NSW 2015, Australia
{*saeed.bastani, lavy.libman, s.waller*}@*unsw.edu.au*

***Abstract*—Intelligent transport information systems (TIS) are one of the most rapidly emerging applications of wireless vehicular communications using DSRC/WAVE technology. A core function in a TIS is the estimation of *traffic density* using beacons transmitted by individual vehicles, subsequently used for purposes such as traffic light control or incident detection. In this paper, we conduct an in-depth study on how the accuracy of traffic density estimation depends on various parameters of the wireless beacons transmission policy, such as beaconing rate and timing. Unlike many other studies, our focus is entirely on the application-layer metric of density estimation accuracy, rather than low-layer metrics such as packet loss rate and throughput. Our results are evaluated over a wide range of traffic traces generated by a commercial microscopic traffic simulator (Paramics), corresponding to a typical urban scenario consisting of a signalized intersection of multiple-lane roads.**

## I. INTRODUCTION

Wireless communications among vehicles and road infrastructure are emerging as an enabling technology for a wide range of novel applications, ranging from road safety to traffic information and entertainment [1]. Much of the progress in this space is enabled by the Direct Short-Range Communications (DSRC) family of standards, including the adaptation of IEEE 802.11 PHY/MAC for the road environment (formerly the 802.11p extension, now incorporated into the 802.11-2012 standard [2]) and the IEEE 1609 Wireless Access in Vehicular Environments (WAVE) standards for higher layer functionalities, covering issues from channel access to message security [3]. The DSRC/WAVE technology and its applications have attracted growing interest from the research community as well as industry and government transportation departments.

In this work our focus is on the use of DSRC for intelligent Traffic Information Systems (TIS). While some earlier studies have considered the feasibility of TIS using cellular communications [4], [5], the use of DSRC allows potentially much more fine-grained traffic information to be collected in real time, using frequent short-range transmission of position beacons from vehicles. Some of the proposed system architectures based on this concept include the Self-Organizing TIS (SOTIS) [6] and TrafficView [7], which generally assumed regular beacon transmissions. More recently, the Adaptive Traffic Beacon (ATB) protocol [8] showed the benefit of allowing vehicles to adapt their beaconing rate according to the channel quality as well as the perceived "message utility", or the amount of new information contained in a beacon message.

In all of the above studies, the evaluation of the proposed techniques and protocols focused on performance metrics such as message throughput or packet loss rate, i.e. metrics that can be measured on the wireless communication layers. This is despite the fact that the purpose of the beacon messages is not similar to any other traditional application of point-to-point or broadcast communication. Rather, the goal of the beacon transmissions is to gather accurate information about the traffic flow on the road, such as the traffic density in different locations, lanes and directions; this information is ultimately used towards traffic control decisions such as timing of traffic light signals [9], and the efficiency of the communication protocols should be measured in terms of the accuracy of the traffic density estimates and the utility of the decisions taken at the application layer.

Motivated by the above, in this paper we conduct an in-depth simulation study to shed light on how the accuracy of the traffic density estimation depends on the operational parameters of the wireless beaconing protocol. More specifically, using traffic traces generated by Paramics, a commercial microscopic car-following traffic simulator, we recreate the mobility pattern in the OMNET++ network simulator where the nodes (cars) transmit beacons, which are then received by a nearby roadside unit (RSU). The RSU then counts the number of beacons received from distinct individual vehicles with a predetermined estimation period. We compare the result of the RSU estimation with the actual traffic traces, and investigate how the density estimation accuracy (i.e., the difference between the estimated and real number of vehicles, expressed in terms of the mean percentage error over time) depends on the frequency of the beacon transmissions, the amount of random jitter applied to the timing of the beacons, and whether or not carrier sensing is done before a beacon transmission attempt. In particular, our findings indicate that the estimation accuracy can be rather unsatisfactory when default parameter values from the DSRC/WAVE standard are used, with up to 10% difference between the estimated and real number of vehicles

‡NICTA is funded by the Australian Department of Communications and the Australian Research Council through the ICT Centre of Excellence program.

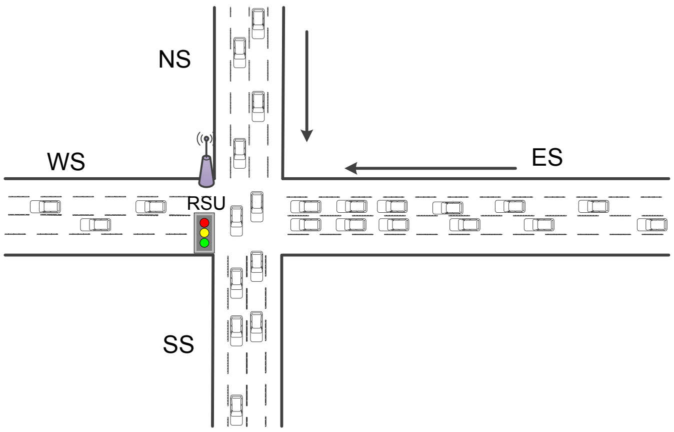


Fig. 1: Traffic scenario

in the RSU range. We show how the accuracy can be improved substantially with better transmission settings, while at the same time reducing the beaconing load and freeing up the wireless channel for other uses.

The rest of the paper is structured as follows. Section II explains our system model and assumptions and describes the simulation framework used in our study. Section III provides a 'baseline' evaluation of the accuracy performance of a simple density estimation algorithm, based on the counting of received beacon messages, under default parameter values from the DSRC/WAVE standard. Section IV presents an in-depth discussion of the impact of the various parameters on the estimation accuracy and concludes with the optimal combination of settings for the traffic estimation application. Finally, Section V concludes the paper.

## II. Simulation framework

We investigate the effects of key DSRC/WAVE parameters on the performance of traffic density estimation through extensive simulations. Our simulation framework is comprised of a traffic and a network simulation component. These components are coupled via mobility traces, generated by the traffic simulator for a scenario of interest and fed into the network simulator employed to simulate vehicle-to-infrastructure (V2I) communications. We use the Paramics traffic micro-simulator, coupled with the Veins framework for the network simulation [10]. Veins is an implementation of DSRC/WAVE protocol stack and relies on MiXiM for the physical layer modeling and OMNeT++ for discrete event simulation.

Our traffic scenario consists of a signalized intersection with four road segments representing the basic blocks of an urban traffic network (Figure 1). The traffic flows associated with the horizontal and vertical road segments are assumed to be unidirectional and are set to near-saturation levels, determined according to the capacity of the intersection. These traffic flow settings correspond to perfect operation of the signalized intersection. As a typical setting for major roads in urban environments, we set the traffic light timing of $t_{cycle} = 100$, $t_{red} = 50$ and $t_{green} = 50$ seconds, speed limit of 20m/sec, and average driver reaction time of 1 sec. Other relevant traffic parameters corresponding to our scenario are shown

TABLE I: DSRC/WAVE and traffic scenario parameters and configuration values

| | Parameter | Value |
|---|---|---|
| DSRC/WAVE | Frequency | 5.89 GHz |
| | Transmission power | 2 mW |
| | Reception power threshold | -89 dBm |
| | Device sensitivity | -89 dBm |
| | Noise power | -110 dBm |
| | Data rate | 18 Mbps |
| | Slot time ($\sigma$) | 13 $\mu s$ |
| | CCH/SCH interval | 50 ms |
| | Guard interval | 4 $\mu s$ |
| | Beaconing Interval (BCI) | 0.1, 0.3, 0.5, 0.7 and 1 sec. |
| | Beacon message length | 500 bytes |
| Traffic Scenario | Road length | NS-SS: 1.7 km |
| | | WS-ES: 2.2 km |
| | Lanes | NS-SS: 2-lane |
| | | ES-WS: 3-lane |
| | Traffic flow | NS $\rightarrow$ SS: 1800 veh/h |
| | | ES $\rightarrow$ WS: 2700 veh/h |
| | Traffic light timing | cycle = 100 sec. |
| | | red = 50, green = 50 sec. |
| | Driver reaction time | 1 sec. |
| | Speed limit | 20 m/s (72 km/h) |
| Channel Model | LOS | Free Space |
| | NLOS | Obstacle Model [11] |
| Simulation | Density estimation interval | 1 sec. |
| | Simulation time | 100 sec. |
| | Number of runs per BCI | 50 |

in Table I. While the above scenario is sufficiently simple to allow an in-depth study of the effect of communication aspects on the performance of the density monitoring application, it represents a typical scenario with key traffic features arising in any urban environment.

The DSRC/WAVE parameters corresponding to the vehicles and RSU are configured as shown in Table I. The beacon queue length in the MAC layer of each node (vehicle) is set to 1, and a new beacon arriving from the application layer replaces the existing beacon in the MAC queue. The RSU, which is located at a corner of the intersection, receives beacon messages from the vehicles in its communication range and estimates the traffic density by counting the number of unique beacons received within a density estimation interval (which is set to 1 sec). In this context, the estimation error corresponding to a given estimation interval is calculated as $err = \frac{k_{trc} - k_{sim}}{k_{trc}}$, where $k_{sim}$ and $k_{trc}$ are the density estimated by the RSU and the actual density of the traffic traces, respectively.

In the experiments, we explore the impact of a number of key aspects of the wireless beaconing protocol, as follows:

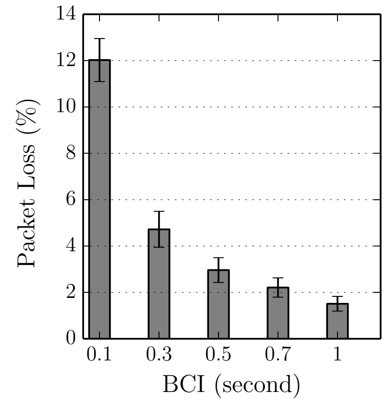
- *Beacon Interval (BCI)*: according to the reference DSRC/WAVE standard, the beaconing rate from each car should be in the range of 1–10 Hz, equivalent to 0.1–1 second beacon intervals. To cover the recommended range, our experiments are conducted using 5 different BCIs in the set $\{0.1, 0.3, 0.5, 0.7, 1\}$ second.

- *Channel Switching (CSW)*: the need for channel switching in the MAC layer depends on the number of radio transceivers and the number of different channels used for safety and data packets. In the most basic form, there is a single radio and two different channels, i.e. a control channel (CCH) and a service channel (SCH). In this case, channel switching is unavoidable and the MAC layer is required to alternate between the two channels according to the predefined CCH and SCH intervals and a guard time specified by the standard (Table I). If there are dedicated radios for safety and data transmissions, channel switching is not required.
- *Beacon transmission timing*: the DSRC/WAVE standard recommends that beacons be transmitted on a regular basis. In addition to this standard scheme, we test another case where the timing of each transmission is shifted by a random jitter of $r \times$ BCI, where BCI is the nominal beacon interval and $r$ is sampled from a uniform random distribution between $[-0.5, 0.5]$. Thus, the random jitter does not affect the long-term average rate of one beacon per BCI. In both the regular and the jittered scheme, the time of the first transmission is chosen randomly, to avoid any unintended synchronization effects among vehicles.
- *Carrier Sense (CS)*: although carrier sensing is a hard-wired feature of the DSRC/WAVE physical layer, its operation is significantly affected by the adverse signal propagation environment. We investigate the impact of carrier sensing on the application performance by considering two extreme cases: a) carrier sensing with minimum sensitivity threshold, equal to the reception threshold (i.e. -89 dBm), which suppresses all concurrent transmissions among vehicles within each other's communication range (though does not prevent collisions due to hidden terminals); and b) carrier sensing switched off, representing an extreme worst-case situation where the adverse signal propagation environment does not allow cars to overhear each other's transmissions at all.

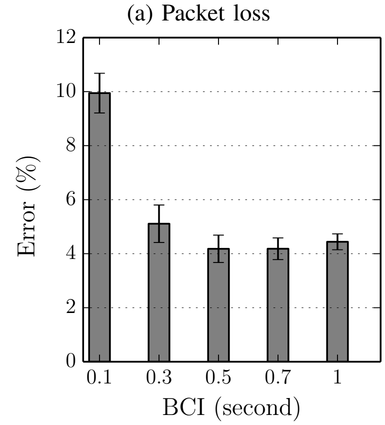
## III. Estimation with default parameter settings

We first test the estimation performance under the default settings stipulated by the DSRC/WAVE standard. Specifically, the channel switching and carrier sensing functionalities are activated and beacons are transmitted regularly. With this setting, we investigate the application performance under various beaconing intervals.

Figure 2 shows the mean packet loss rate and density estimation error at the RSU, with 95% confidence intervals. The mean estimation error is obtained as an average error across all estimation intervals (1 sec each), where the error in each interval is calculated as defined in section II, i.e. the difference between the estimated and the true vehicle density, expressed in relative (percentage) terms. The values in both Figure 2a and 2b are obtained by averaging the respective metrics over the individual runs corresponding to each BCI.




(a) Packet loss




(b) Density estimation error

Fig. 2: Packet loss and density estimation error with default parameter settings

We observe from Figure 2a that the packet loss rate increases monotonically with decreasing BCI, which is explained by the increasing rate of beacon packets destroyed by collision. Notably, the span of packet loss rates is considerable in our scenario, rising from 2% for BCI=1 sec to 12% with BCI=0.1 sec; this suggests that the collisions are a dominant cause of packet losses, compared to random losses due to channel conditions (which are not affected by beaconing rate).

The behavior of the density estimation error in Figure 2b is more interesting. Here, the estimation error generally follows the same trend as the raw loss rate of beacon packets for BCI$\leq$0.5 sec. However, for BCI between 0.5 and 1 sec, a different effect comes into play, which in fact causes the estimation error (in percentage terms) to be higher than the rate of packet losses. To understand this effect, consider that the RSU counts the number of unique beacons in each estimation interval, which is 1 sec in duration. However, the population of cars within the communication range of the RSU does not remain static; some cars move into the said range while others depart from it within the estimation interval duration. While the number of cars at the edge of the communication range is highly variable and traffic-dependent, a rough estimate from the average flow rates in our scenario (1800 veh/h and 2700 veh/h in the North-South and East-West flows, respectively) yields that, in an average 1 sec period, 0.5+0.75 new vehicles enter the range while the same number of vehicles depart on the other side. Depending on the precise timing of their beacon transmissions, any of these vehicles may or may not end up being counted during the estimation period. As the total number of vehicles within the RSU communication range under the traffic parameters in Table I is typically around 20–25, this quantization effect implies that, even without packet losses, the average error of a simple beacon-counting estimation strategy cannot go below a lower bound of approximately 4%.

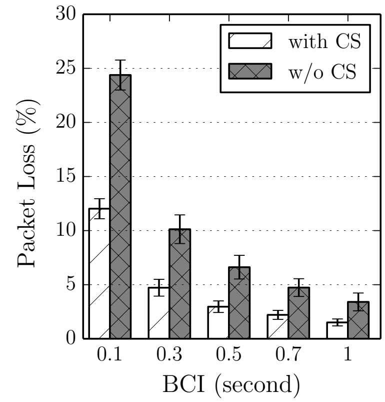
Apart from the above effect, we note that, when the BCI is between 0.5 and 1 sec, more frequent beacons slightly improve the estimation accuracy, since if a transmission fails, the node will sometimes manage to send another beacon and be counted by the RSU within the same interval. However, in scenarios with BCI≤0.5 sec, more frequent beacon transmissions end up increasing the density estimation error due to the far higher collision rate. These observations imply that, in our road scenario and with beaconing protocol settings as per the standard default, the optimal BCI is not found at the extreme ends of the nominal range but somewhere in the middle.

## IV. Impact of transmission parameters on estimation accuracy

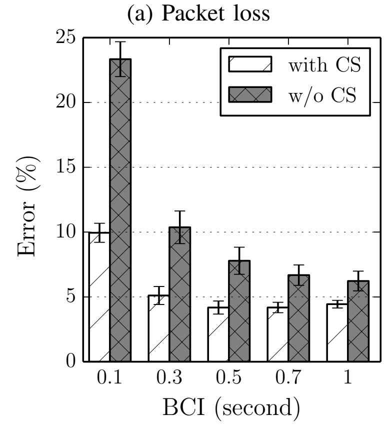
In this section, we investigate the impacts of the aforementioned aspects — namely, channel switching and beacon transmission timing (which can be controlled by the nodes), as well as carrier sensing (which depends on the signal propagation environment) — on the packet loss rate and density estimation error, and compare them with those achieved with the default settings. To gain a clear understanding of the impacts of each of these parameters, we first explore each of them individually, before reaching a conclusion about their best combination.

### *A. Carrier sensing*

We first address the effect of carrier sensing while keeping the channel switching and beacon timing in their default settings. Thus, we compare the results from Section III with the case where the physical-layer carrier sensing functionality is deactivated, equivalent to a situation in which vehicles are unable to overhear each other. In Figure 3, these scenarios are referred to as "with CS" and "w/o CS", respectively. It can be seen that, at all BCI values, the lack of carrier sensing ability causes the packet loss rate to be roughly doubled. The resulting effect on the density estimation error is not uniform, however. As explained in Section III, for BCI values above 0.5 sec, the packet losses are not the main factor contributing to the estimation error; thus, even a double loss rate has only a mild impact on the estimation accuracy. On the other hand, with BCI=0.1 sec, the higher packet loss rate leads to a very high estimation error. This is partly due to the fact that, with a regular beaconing period and without carrier sensing ability, colliding beacons from any two vehicles will continue to collide repeatedly in all subsequent retransmissions as long as both vehicles remain within the RSU communication range. Thus, the benefit of higher beaconing frequency in combating losses due to random noise is more than negated by the increased rate of packet collisions.




(a) Packet loss




(b) Density estimation error

Fig. 3: Impacts of carrier sensing functionality

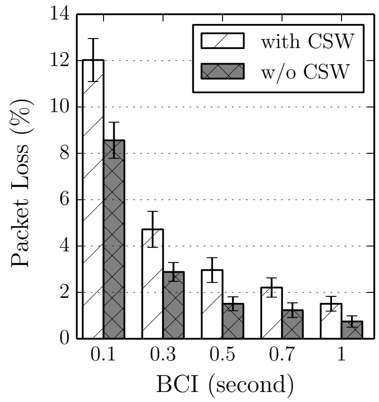
We point out that, even with active carrier sensing, collisions from hidden nodes (i.e. vehicles from opposite ends of the RSU's communication range, which cannot hear each other) cannot be avoided.† We leave a detailed study of the impact of hidden-node collisions on the estimation accuracy for future work; however, in general, we expect that their impact grows (and, thus, the relative importance of carrier sensing diminishes) with the network dimensions, e.g. number of lanes and road segments.

Similar trends to those of Figure 3 occur with other combinations of channel switching and beacon timing, and owing to space limitations we omit the corresponding figures.

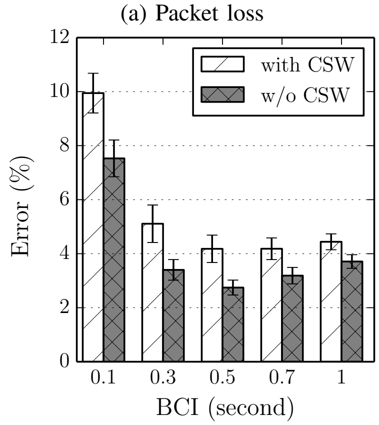
### *B. Channel switching*

In this experiment, we address the effect of channel switching on the packet loss rate and density estimation error, while keeping the default (regular) beacon timing scheme as described in Section III. Figure 4 shows the experiment results with 5 different BCIs. We observe that the results in the scenario without channel switching follow a similar shape and trend to that with channel switching. However, in the absence of channel switching, the packet loss rate and estimation error

†The hidden node problem is generally tackled in IEEE 802.11 by employing RTS/CTS handshakes ahead of transmission of data packets; however, this technique is not relevant for broadcast packets used for traffic beaconing.

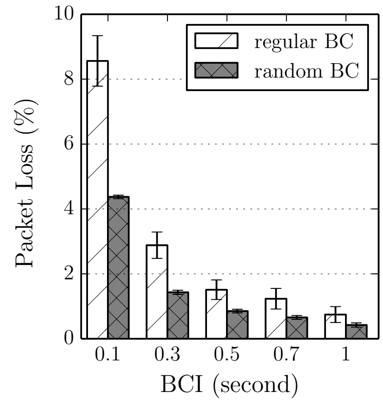



(a) Packet loss

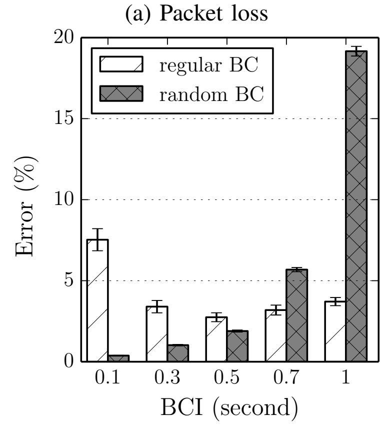



(b) Density estimation error

Fig. 4: Impacts of channel switching




(a) Packet loss




(b) Density estimation error

Fig. 5: Comparison of regular and random BC (active carrier sensing, no channel switching)

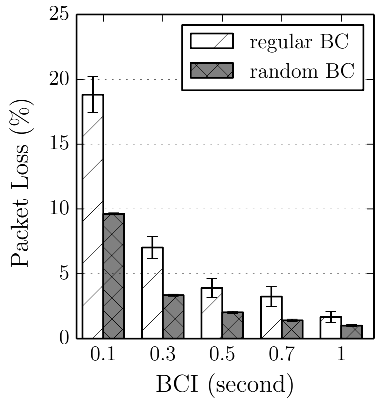
decrease considerably — e.g., in the most frequent beaconing regime (BCI=0.1 sec), the raw beacon loss rate drops from 12% to 8.5%, while the ultimate estimation error improves from 10% down to 7.5%. This is attributed to the fact that the effective channel load decreases if the MAC layer does not need to alternate between multiple channels. In other words, with channel switching, a node has to send the same number of beacons in half the time (and even slightly less, due to switching overheads), resulting in a higher rate of beacon collisions and lower scalability to a large number of cars.

### *C. Randomization of transmission timing*

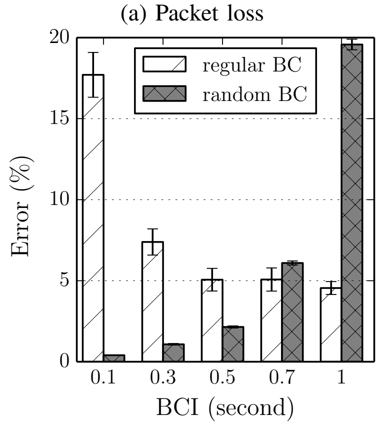
Consider a situation where two mutually hidden nodes (i.e. cars that are unable to hear each other's transmissions) transmit a beacon at the same time, thereby causing a collision at the RSU. If the beacons are transmitted at regular intervals, then further transmissions from these nodes will continue to collide repeatedly; thus, even if the beacons are retransmitted many times in each estimation interval, these nodes do not end up getting counted by the RSU. We therefore expect that adding a random jitter to the timing of each beacon transmission, of up to half of the beaconing interval, will significantly improve the probability of at least one beacon to avoid a collision, and hence the accuracy of the beacon counting. It should be highlighted that, even though a small amount of random jitter happens automatically due to the backoff procedure of the IEEE 802.11 DCF, the latter is negligible (under 802.11 standard parameters it only shifts the transmission time by a small random number of 50 $\mu$sec slots, much less than the beacon packet duration), and does not make any difference when the nodes are beyond each other's carrier sensing range.

This effect is indeed confirmed in Figures 5 and 6, which show the performance achieved with randomized timing of beacon transmissions, with and without carrier sensing, respectively. For small values of BCI ($\leq$ 0.5 sec), we observe that, while the packet loss rate decreases somewhat, the ultimate estimation error drops markedly. On the other hand, when the BCI is more than half of the estimation interval, the timing randomization becomes counterproductive: it leads to a situation where, in each estimation interval, a certain fraction of nodes do not make a beacon transmission at all within the duration of that interval. Such nodes are not counted and thus lead to an increase in the average estimation error, despite the lower packet loss rate due to collisions.

In summary, the observations of the experiment results reported in this section suggest that the optimal parameter setting, in the sense of minimizing the density estimation error, are: a) no channel switching (i.e. a dedicated radio transceiver for the traffic monitoring application); and b) random timing of beacon transmissions if they are made frequently (i.e. BCI is low), otherwise regular periodic transmissions for BCI that are above half of the estimation interval. For convenience, Figure 7

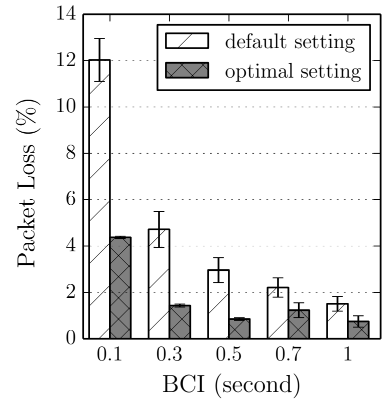



(a) Packet loss

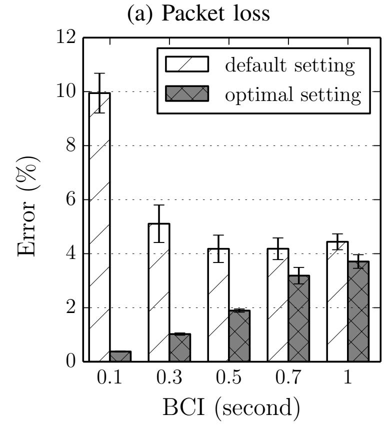



(b) Density estimation error

Fig. 6: Comparison of regular and random BC (no carrier sensing, no channel switching)




(a) Packet loss




(b) Density estimation error

Fig. 7: Default vs. performance-aware parameter setting

summarizes the packet loss rate and density estimation performance as a function of the beaconing frequency, assuming optimal parameter settings. Notice that, while the lowest error rate achievable under default standard protocol settings is around 4%, the optimal application-cognizant parameter settings can bring it down to under 1%.

## V. Conclusion

We have investigated the performance of traffic density estimation using wireless beacons, an essential component of any DSRC-based traffic information system. Specifically, we explored the impact of wireless protocol parameters and showed that, in order to achieve a good accuracy, the method requires a very high beaconing rate, as well as a random jitter in the beacon transmission timing. A possible approach to reduce the required beaconing rate using kinematic information, namely, drawing on well-established relationships between vehicle speeds and traffic density from traffic modeling theory, is currently the subject of ongoing work.

## References

[1] T. Willke, P. Tientrakool, and N. Maxemchuk, "A survey of inter-vehicle communication protocols and their applications," *IEEE Communications Surveys and Tutorials*, vol. 11, no. 2, pp. 3–20, 2009.

[2] "IEEE 802.11-2012 standard for information technology — telecommunications and information exchange between systems — local and metropolitan area networks — specific requirements — part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," 2012.

[3] "IEEE 1609 — standards for wireless access in vehicular environments (WAVE)."

[4] J. Rybicki, B. Scheuermann, M. Koegel, and M. Mauve, "PeerTIS — a peer-to-peer traffic information system," in *Proc. ACM International Workshop on Vehicular Internetworking (VANET)*, Beijing, China, Sep. 2009.

[5] C. Sommer, A. Schmidt, Y. Chen, W. Koch, and F. Dressler, "On the feasibility of UMTS-based traffic information systems," *Ad Hoc Networks*, vol. 8, no. 5, pp. 506–517, Jul. 2010.

[6] L. Wischhof, A. Ebner, H. Rohling, M. Lott, and R. Halfmann, "SOTIS — a self-organizing traffic information system," in *Proc. IEEE Vehicular Technology Conference (VTC)*, Jeju, South Korea, Apr. 2003.

[7] T. Nadeem, S. Dashtinezhad, C. Liao, and L. Iftode, "TrafficView: Traffic data dissemination using car-to-car communication," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 3, pp. 6–19, Jul. 2004.

[8] C. Sommer, O. Tonguz, and F. Dressler, "Traffic information systems: efficient message dissemination via adaptive beaconing," *IEEE Communications Magazine*, vol. 49, no. 5, pp. 173–179, May 2011.

[9] M. Ferreira, R. Fernandes, H. Conceição, W. Viriyasitavat, and O. Tonguz, "Self-organized traffic control," in *Proc. ACM International Workshop on Vehicular Internetworking (VANET)*, Chicago, USA, Sep. 2010.

[10] C. Sommer, R. German, and F. Dressler, "Bidirectionally coupled network and road traffic simulation for improved IVC analysis," *IEEE Transactions on Mobile Computing*, vol. 10, no. 1, pp. 3–15, Jan. 2011.

[11] C. Sommer, D. Eckhoff, R. German, and F. Dressler, "A computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments," in *Proc. IEEE/IFIP Conference on Wireless On-demand Network Systems and Services (WONS)*, Bardonecchia, Italy, Jan. 2011.