Context-Aware Channel Coordination for Vehicular Communications

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Abstract

Vehicular communication could be the much anticipated breakthrough against the unabated fatal and near fatal accidents that continue to threaten the public safety on our roads. The same technology is also expected to concurrently support a range of non-safety applications including real-time traffic information, mobile entertainment, and access to the Internet. The standard has specified an explicit multi-channel structure whereby safety and non-safety transmissions will occur at different channels. Consequently, a vehicle with a conventional single-radio transceiver will need to continuously switch between the safety and the non-safety modes of operation. The interval spent in the safety mode (safety interval) at each cycle is a critical parameter that directly limits the availability of the technology for commercial use. Using simulation, we show that the safety interval required to satisfy the reliability of safety applications is a function of traffic density on the road. Given that in most roads traffic density is expected to vary during the day, we propose dynamic adjustment of the safety interval based on the traffic context. To further motivate the concept of traffic aware vehicular communications, we evaluate the performance of three dynamic channel coordination algorithms using empirical traffic data collected from the roads around the city of Sydney, Australia. A key finding is that, the time-of-day is an effective context that can prevent a vehicular radio from keep running in the safety mode unnecessarily, thereby enhancing the commercial opportunity of the technology. We further demonstrate that the use of the location context can dramatically improve the performance of the basic time-of-day algorithms.

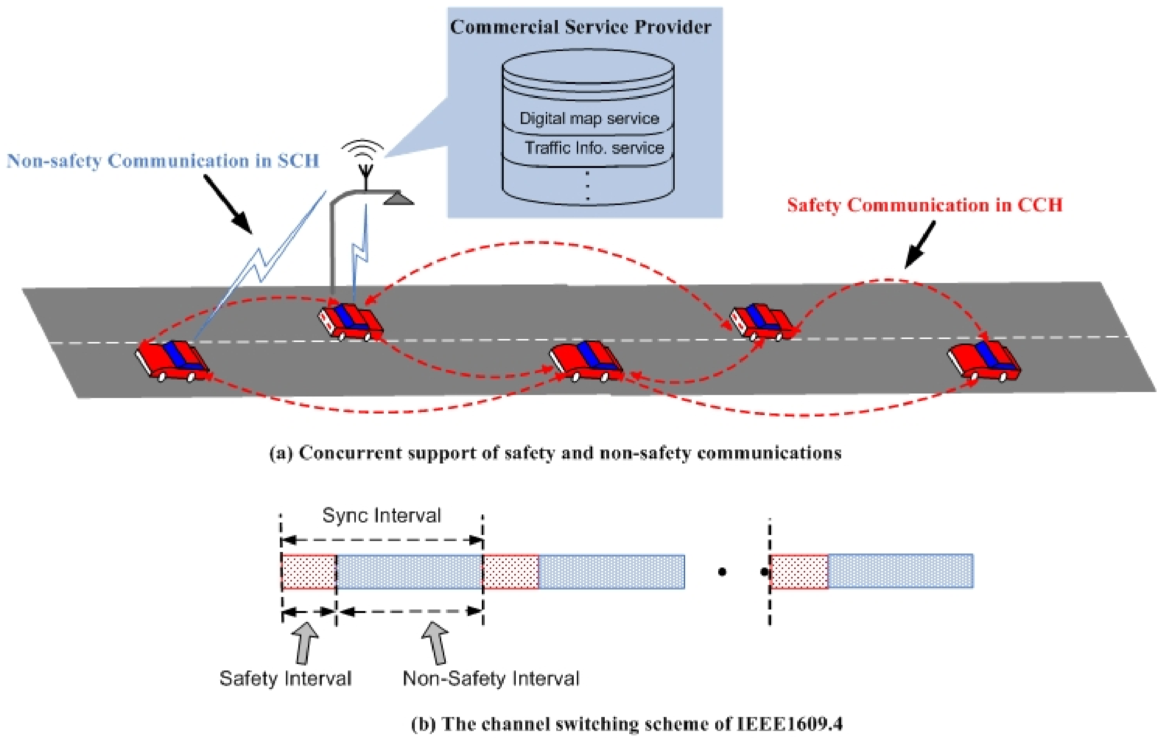


Figure 1: A typical vehicular communication scenario in the future

1 Introduction

Figure 1(a) shows a typical vehicular communication scenario of the future. Cars are equipped with short range radio transceivers which allow them to communicate directly with other nearby cars. By frequently exchanging the location and other vehicular status information with each other, cars are able to detect a potential crash well before it happens. By activating appropriate warnings to the driver, these radio-equipped cars can prevent most of the fatal accidents that occur in today's roads. This is the safety part of the vehicular communications. The vehicles would also communicate with roadside infrastructure for a range of entertainment, commercial, and traffic related transactions. Examples of such non-safety activities include high-speed tolling, digital map downloading, receiving real-time traffic information, and accessing the Internet. Vehicular communications therefore is seen as a key enabling technology of the future that will dramatically improve the safety and efficiency of our transport systems.

To accommodate both safety and non-safety over the same vehicular spectrum, the current Dedicated Short Range Communication (DSRC) standard divides the spectrum into seven non-overlapping channels. Safety communication is generally restricted to the control channel (CCH)[1]. All non-safety data transfers are carried out in one of the 6 service channels (SCHs). The multichannel structure raises an interesting issue though. Since conventional radios are not capable of transmitting (or receiving) over multiple channels *simultaneously*, they must switch back and forth between the CCH (safety mode) and the SCHs (non-safety mode).

[1]The CCH could be used by commercial service providers occasionally for advertising non-safety services.

The channel switching architecture adopted by the IEEE 1609.4 [2] standard is shown in Figure 1(b). In every Sync Interval, which is about 100ms for practical vehicular situations, the radio switches to the control channel for exchanging safety messages with nearby vehicles. After staying in the CCH for a predefined interval (safety interval[2]), the radio is allowed to switch back to any SCH it may be interested in.

The safety interval is a critical parameter that directly affects the radio time (resources) occupied by safety communications. The larger the interval, the less radio resources available for non-safety activities. Obviously, the interval has to be long enough to meet the safety requirements. In this article, we show that the safety interval required to satisfy the reliability of safety communications is a function of traffic density around the vehicle. Given that in most roads traffic density is expected to vary during the day, we propose and motivate dynamic adjustments of the safety interval based on the traffic context. Using the empirical traffic data collected from the roads around the city of Sydney, Australia, we reveal that simple time-of-day adjustments of the safety interval can free up hours of radio time.

2 Safety Interval and Traffic Density

As a first step towards motivating the concept of context aware channel coordination, we investigate the impact of traffic density on the length of safety interval required to achieve a given reliability. The reliability is defined as the probability that transmitted messages are received without error by the nearby vehicles. Our investigation is carried out using a series of simulation experiments[3] on a 6-lane road. Figure 2 presents the simulation results.

Figure 2(a) shows two important results. It tells us that for a given traffic density, reliability increases as a function of the safety interval. More importantly, it shows that for a given safety interval, lowering the traffic density increases the reliability. The implication of this result is depicted in Figure 2(b), which shows that for a target reliability for safety communications, the safety interval is an increasing function of the traffic density. For example, if 90% reliability is desired, a safety interval of only 10ms is sufficient for a traffic density of 10 veh/km, whereas the interval has to be twice as long if density increases to 70 veh/km.

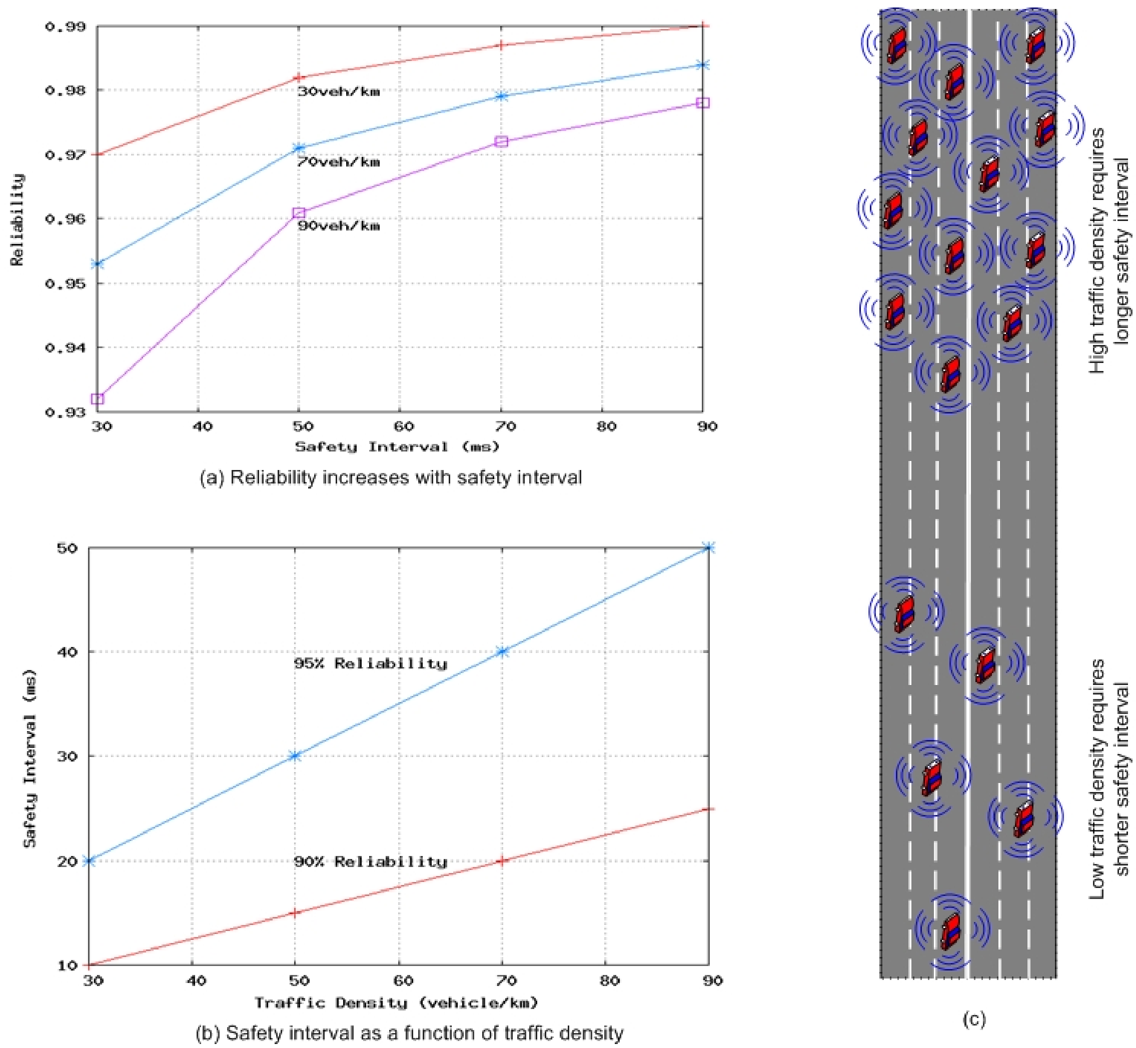
The dependency of the safety interval on the traffic density as revealed by the simulation experiments has an intuitive explanation. The DSRC standard uses a random access MAC protocol (IEEE 802.11p [1]) where it is possible for transmissions from two or more vehicles to overlap in time. When such overlap occurs, the receivers might not correctly decode the received signal causing a loss of safety messages (reducing the reliability). The more vehicles contending for the channel, the greater the probability of overlaps [4]. However, with a larger safety interval, vehicles can spread their transmission attempts over a longer time interval, minimizing the possibility of overlaps.

The fact that the safety interval is a function of the traffic density motivates us to consider channel coordination schemes that dynamically adjust the safety interval based on the traffic context (density in this case). Before we examine possible ways to achieve such dynamic adjustments of the safety interval, let us first take a look at some real traffic data and see how traffic density varies over time and space.

[2]Note that when the vehicles switch to the control channel, they must stay in that channel long enough for all nearby vehicles to complete the exchange of their status messages with each other.

[3]The details of the simulation experiments can be found in [9]

[4]Other researchers have also observed high loss rates in vehicular communication simulations with congested channels [3, 5]



(a) Reliability increases with safety interval

(b) Safety interval as a function of traffic density

(c)

Figure 2: The Relationship between the safety interval and the traffic density

3 Traffic Data From Sydney Roads

The traffic flow, also known as traffic volume, which is measured as the number of vehicles passing a certain location in an hour, is a very useful information for traffic control and management. Most road and traffic authorities routinely measure the traffic flow data. With the help of traffic theory, the flow data can be used to estimate the traffic density on the roads.

3.1 Site Description and Flow Data

Sydney, the state capital of New South Wales (NSW), is the most populous city in Australia. The city has a large and complex road network serving millions of vehicles per day. The Road and Traffic Authority (RTA) of the State of NSW, has been undertaking traffic flow surveys in the Sydney region for many years. Some of the traffic flow data has been released for public use [7]. The traffic flow data is collected by pneumatic counters counting the number of vehicles passing the survey location. The data are recorded for each hour of a day. For each survey

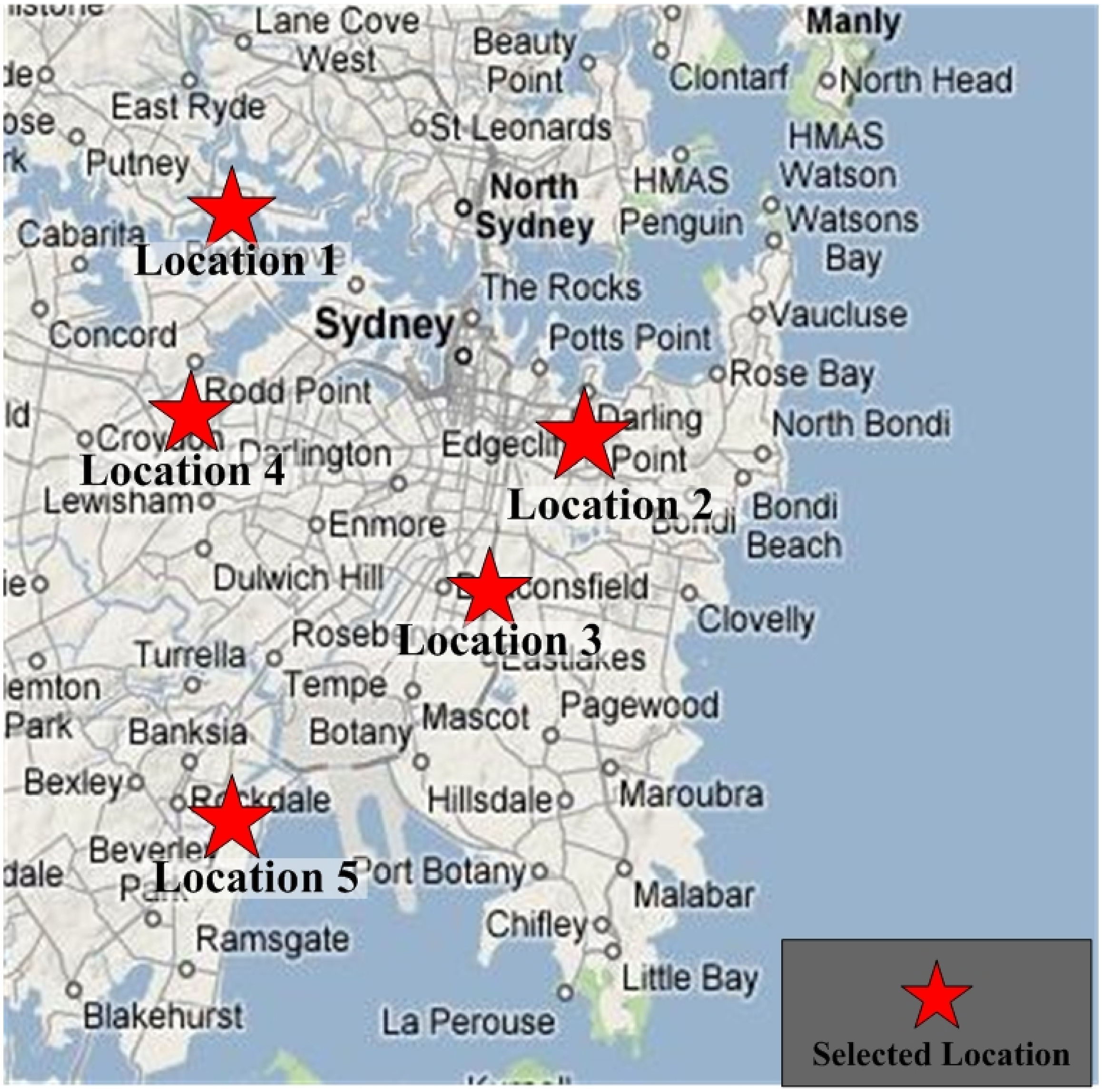


Figure 3: Five locations selected from the suburbs of Sydney (source: Google Map)

location, the flow of the traffic towards two opposite directions are measured separately (Q_1 and Q_2).

Out of many survey sites around Sydney, we selected five sites (see Figure 3) to get a feel for how the traffic density varies over time and space. Some of the guidelines used for the selection of the sites are as follows:

- All sites are located in the suburban areas where the traffic generally flows well without experiencing severe congestions.
- The distance between any two of the selected sites is at least several kilometers so that the traffic flows are independent with each other.
- Number of lanes (6-lane) and speed limit are identical for all sites.

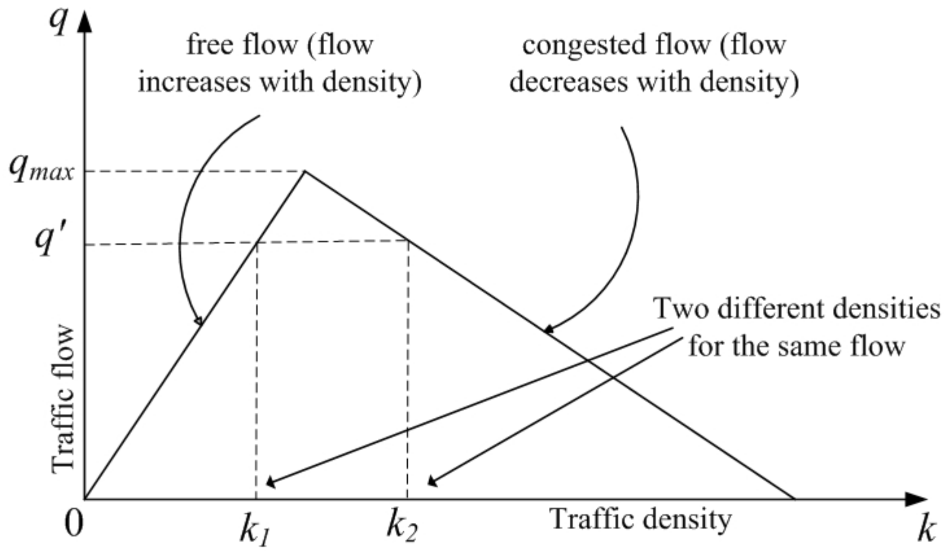


Figure 4: The relationship between the traffic flow and traffic density

3.2 Traffic Theory: Flow to Density

The traffic flow q, density k and speed u are the key quantities to study the traffic characteristics and road capacity. The relationships between these three quantities have been explored and modeled by the traffic flow theories for years. Recently, with the increasing interest in the wireless vehicular communications, these theories are also becoming valuable tools for the vehicular network design.

Given that a low traffic flow can be due to a lack of vehicles on the road or because of heavy congestion, according to the traffic theory, a typical flow-density (q-k) relationship follows the general shape in Figure 4. The curve is composed of two parts, namely *free flow* and *congested flow*. When density is low, traffic flow increases with density. After traffic flow reaches the maximum value, higher density will cause congestion so flow is reduced with further density increasing.

Such a flow-density relationship shows that for a given traffic flow, there are two possible traffic densities, located in the *free flow* and *congested flow* regime respectively. However, the survey sites selected to collect traffic flow data are all located in suburban areas where traffic generally flows well without severe congestion. Therefore, to estimate trafic density for the traffic flow data considered in our study, we use the *free flow* regime.

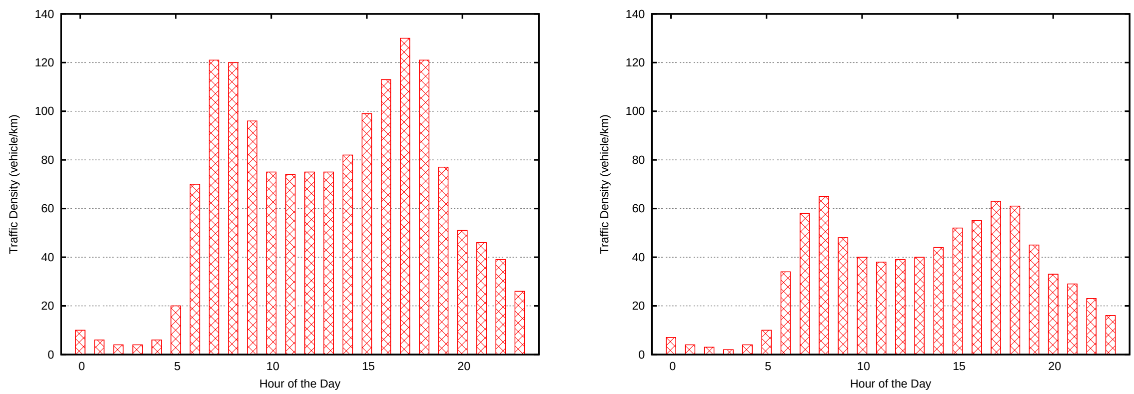
Under the *free flow* condition, if it is assumed that vehicles traveling along a road are evenly spaced and at the same speed u (km/hr), the traffic density k (veh/km) and the traffic flow q (veh/hr) have the following relationship [4]:

$$k = \frac{q}{u} \tag{1}$$

By replacing q with $Q_1 + Q_2$ in Equation (1), we can approximately estimate the traffic density across all the six lanes. To study the typical traffic density at different time of a day, the hourly traffic densities are calculated by taking the average of the same time in five weekdays.

Figure 5 shows the estimated traffic densities of two locations out of the 5, which has the highest and lowest density respectively. It is observed that the traffic densities have three distinct levels during a day. In peak hours(6:00-9:00 and 15:00-19:00), the densities are the highest, in night hours (0:00-5:00), the roads have lowest densities, and the densities of the off-peak hours (10:00-14:00 and 20:00-23:00) are in the middle of the previous two. This three level pattern are found in all the five selected locations.

Another finding is that although the density changing patterns are similar for all locations, the actual densities vary across all locations. For example, we can see in Figure 5 that, most of the non-peak hour densities of Location 1 are actually higher than even the peak hour densities of Location 2. Clearly, traffic density is a parameter that is far from static. Even with only 5 locations studied, we find it highly dynamic in both time and space.



(a) Location 1 (b) Location 2

Figure 5: Traffic density variation in time and space

4 Context-aware Channel Coordination

For static channel coordination schemes not designed to be context-aware, the safety interval has to be long enough to cater for the worst possible traffic situation, i.e., the highest possible traffic density in a given service area. Given the significant variations in the traffic density during the day, the static scheme would force the vehicular radios to operate in the safety mode longer than they should. Since spending any unnecessary time in the safety mode directly limits the availability of the radio for non-safety applications, we explore ways to dynamically adjust the safety interval based on the traffic context.

4.1 Ideal Adjustment with Real-time Density Estimation

By now, it is clear that the traffic density is the primary context governing the optimum value for the safety interval at a given time and location. One straight-forward way to design context-aware systems would be to track the traffic density in real-time and adjust the safety interval whenever significant changes are detected in the traffic. Without worrying about the details of how to estimate the current density in real-time, let us assume that it is possible for all vehicles to synchronously detect the change in traffic density and switch to the new safety interval every hour or so to match the actual density observed on the road. We will refer to this scheme as the *ideal adjustment*. The ideal adjustment may be difficult to realize, but it would serve as the theoretical optimum that could be achieved with context awareness. Next, we explore other auxiliary contexts, namely time-of-day and location, that are rather easier to obtain.

4.2 Time-of-day Adjustment

Based on the traffic density pattern revealed by the empirical data (Figure 5), we can divide the time-of-day into three broad categories, namely peak time, off-peak time and night time. For each time-of-day category, the safety interval corresponds to the highest traffic density in that category across all 5 locations. Compared to the ideal adjustment, the time-of-day adjustment is much simpler to implement because all the vehicles need to obey the identical time-interval rules, peak-time safety interval, off-peak-time safety interval, and night-time safety interval. These rules can be preset into the vehicular radios so no extra overhead is incurred due to context awareness. Obviously, using the time-of-day as a context to estimate actual traffic density is not the most accurate way to track the context. Hence it cannot be expected to meet the performance of the ideal adjustment. We, however, note that many existing traffic control systems either exclusively run on a time-of-day mode or use time-of-day as a backup to real-time or traffic-responsive mode of operation [6].

4.3 Time-of-day Adjustment with Location Awareness

We have seen from our empirical data analysis that traffic density in a given service area varies not only in time, but also in space. For example, in the same time-of-day category of peak hour, Location 1 has a maximum density of 130 veh/km, which is nearly three times the density observed in Location 2 (see Figures 5a and 5b). When such significant differences exist between different road segments in the same service area, simple time-of-day rules for safety interval update becomes less effective. The safety intervals in the low-density roads would be adjusted based on the densities observed in the high-density roads limiting the non-safety communication opportunities in the low-density roads unnecessarily. To overcome this limitation, the location context could be added to the design. Instead of having the universal time-interval rules for the entire service area, the rules could be derived as a profile for specific locations based on the traffic characteristics of the location. With the knowledge of the profiles, the vehicles can update the safety interval based on the time-interval rules in the location profile. With location context built-in, commercial service providers operating at a low-density location would not be disadvantaged by the high density traffic at a distant location.

5 Performance Evaluation

To evaluate the performance of the proposed dynamic safety interval algorithms, we need a metric that represents the daily DSRC airtime in a given location that would be dedicated for safety communications. Let us call this metric the Daily Safety Airtime or DSA. In a given location, the daily DSRC airtime available to a commercial service provider for non-safety communications is then simply derived as $24 - \text{DSA}$. Clearly, for a given traffic pattern in a given location, a channel coordination algorithm is better than another if it results in lower DSA (more airtime available for commercial activities). Since traffic data generally records hourly variations during a 24-hour day, we can compute the DSA by aggregating the hourly airtime data. For each hour i, the time spent in the control channel is the ratio of the safety

Table 1: The safety interval for time-of-day at different locations

Location	peak-time		off-peak time		night time	
	NLA	LA	NLA	LA	NLA	LA
1	65ms	65ms	50ms	50ms	30ms	30ms
2	65ms	40ms	50ms	30ms	30ms	15ms
3	65ms	40ms	50ms	40ms	30ms	15ms
4	65ms	50ms	50ms	40ms	30ms	25ms
5	65ms	50ms	50ms	35ms	30ms	20ms

interval (t_i) to the Sync Interval (T[5]): $\frac{t_i}{T}$. Hence, the DSA equals to $\sum_{i=1}^{24} \frac{t_i}{T}$.

Different algorithms result in different values for the safety intervals. For the static scheme, the safety interval remains the same throughout the day. It has to be set to a value that would meet the desired reliability for safety messaging even during the highest possible traffic density that may be expected in a given service area (a given town or city for example). Let us assume that a 95% reliability is targeted for the Sydney region. Given that the highest density recorded among all the 5 locations is 129*veh/km*, we set the safety interval to 65ms for the static algorithm[6]. For the ideal adjustment, we select a different safety interval every hour in response to the hourly change in traffic density. Finally, Table 1 shows the safety interval values for the basic non-location aware (NLA) time-of-day and the location-aware (LA) time-of-day algorithms.

The DSA for the four channel coordination schemes are compared in Figure 6. It is clear that the dynamic adjustment of the safety interval significantly reduces the airtime 'locked in' for safety communications. While the maximum saving in the DSA is achieved with the ideal (hourly) adjustment of the safety interval in response to the current traffic density, the figure reveals that even the basic time-of-day adjustment without any location-awareness results in a 25% savings. This is remarkable given the simplicity and ease-of-deployment of the time-of-day algorithm. It is interesting as well to note that the performance difference between the time-of-day and the ideal adjustment is much smaller in locations with high traffic density (see Location 1). Another important observation we make is that, by incorporating location-awareness, it is possible to significantly improve the performance of the time-of-day algorithm. This can be particularly useful in low-density locations (see Locations 2 and 3) where time-of-day performs poorly compared to the ideal adjustment.

6 Conclusion and Open Issues

We have studied the problem of channel coordination between the safety and the non-safety applications in vehicular communication. Using empirical traffic data, we have shown that the non-safety use of the vehicular communication can be significantly enhanced by dynamically adjusting the safety interval in response to the varying traffic conditions on the road. We have demonstrated that, the time-of-day is an effective context capable of preventing a vehicle from

[5] In our calculations, we assumed a Sync Interval of 100ms to reflect the finding that most of the vehicular safety applications require a communication frequency of 10Hz [8]. One could use other values, but the qualitative results are not affected.

[6] Note that for a given traffic density, we use simulation experiments to derive the corresponding safety interval.

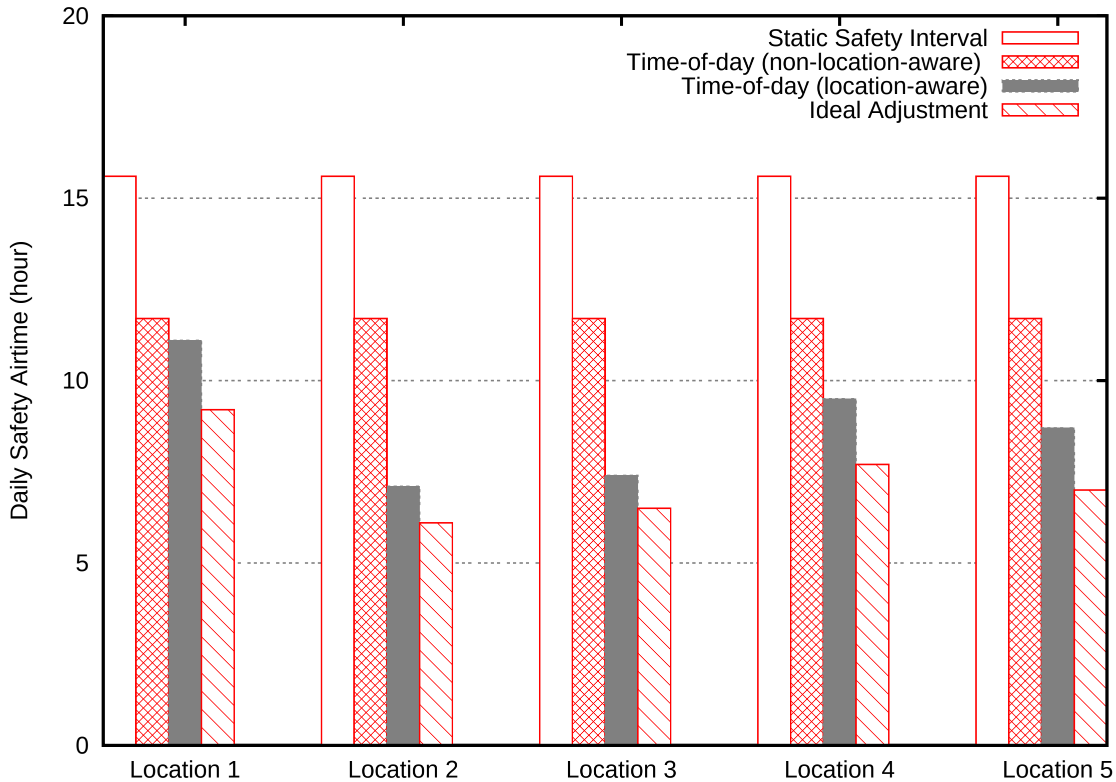


Figure 6: Performance comparison of different channel coordination schemes

'idling' in the safety mode, thereby enhancing the commercial opportunity of the technology. We have further shown that the use of the location context can dramatically improve the performance of the basic time-of-day algorithms. In summary, for dynamic channel coordination in vehicular communication, the combination of the time-of-day and the location of the vehicle may be as effective as the real-time tracking of the traffic condition.

Although we have clearly demonstrated the benefits of the context-aware channel coordination, there remains several issues before the concept can be fully realized. One key issue is the resynchronization of vehicular radios to the new values of the safety interval. Resynchronization is not a significant issue for the basic time-of-day adjustment because of the availability of a common time base for all vehicles using technologies such as the (Global Positioning System)GPS clock. The issue, however, becomes challenging if location is used as a secondary context to achieve different time-of-day adjustments for different locations. When a vehicle crosses the boundary of two adjacent locations having two different recommended safety intervals, it will be 'out of sync' with vehicles that are in the adjacent location, but within the wireless communication range of the radio. How to accomplish a smooth 'handover' in such situations remains an interesting research problem to solve.

7 acknowledgement

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