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The Design of Reliable Protocols for Wireless Traffic Signal System

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The Design of Reliable Protocols for Wireless Traffic Signal System

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Abstract— **Electronic traffic signal has the advantage of being easily visible to machines. It is expected to augment the traditional traffic light system in future intelligent transportation environments, where intelligent vehicles interact with each other and with traffic systems and give informed advisories to drivers. One problem with wireless signals is that they are essentially omnidirectional. Even if one uses directional wireless signaling source, it is not clear how any recipient of a signal can reliably determine whether the signal is meant for him or her, in the presence of signal reflections. In this paper, we present a basic electronic traffic signalling protocol framework and two reliable protocols for intersection traffic signal and stop sign signal. These protocols enable recipient vehicles to robustly differentiate the signal's designated directions despite of potential threats (confusions) caused by reflections. We demonstrate how to use one of the protocol to construct a sample application: a red-light alert system. We also address potential inconsistency threats caused by the uncertainty of location system being usedand discuss means to handle them.**

Keywords— **traffic signal, wireless, protocol, reliable**

I. Introduction

With recent advances in communication, computation and sensor technologies, we can envision moving into a new era of intelligent transportation, where intelligent vehicles sense objects in their proximity, talk to each other, and talk to the traffic control infrastructure, for the purpose of making the transportation system safer, more efficient, and more enjoyable. The Intelligent Transportation System(ITS) program at the US Department of Transportation (USDOT) [1] is an example of government efforts in this direction. Major automakers such as Ford, GM, DiamlerChrysler, Toyota and Nissan are all partners [2] of the intelligent vehicle initiative (IVI) spearheaded by USDOT. This joint effort by automakers and governments around the world are expected to change our perception of intelligent transportation systems dramatically in the future.

This paper presents our work in designing an electronic traffic signal system for the exciting future of intelligent transportation landscape. An electronic traffic signal system wirelessly broadcasts information about traffic lights or traffic signs. The major advantages of an electronic traffic signal system are as follows:

1. Electronic signal is easily machine readable. It is easier and faster to process than visual signal. This is important in time-critical automated vehicle systems.
2. It does not require line-of-sight.
3. It can be used to help visually impaired people. Helps to solve the problem of color-blinded driver or near-sighted driver.
4. It is relatively robust against glare, fog, snow, smoke and heavy rain, which often cause low visibility conditions and accidents.

Improving the traffic safety in roadway intersections was our original goal that led us to pursue a wireless traffic signalling system. Once drivers are able to observe clearly traffic signal under low visibility conditions created by glare, heavy snow, fog etc., we expect related accidents will be reduced. We expect that this kind of wireless signal system will play a key role in future transportation infrastructures.

One major difficulty of designing a wireless traffic signal system lies in the fact that wireless signal are essentially omnidirectional. While it is true that there are directional wireless signal sources (antenna), but potential reflection and deflection of the signal by vehicles, roads, buildings and other objects in proximity can change the direction of wireless signal totally. A car travelling north might pick up the wireless signal "GREEN" meant for the cars travelling east. A simple case is shown in Figure 1. The directional

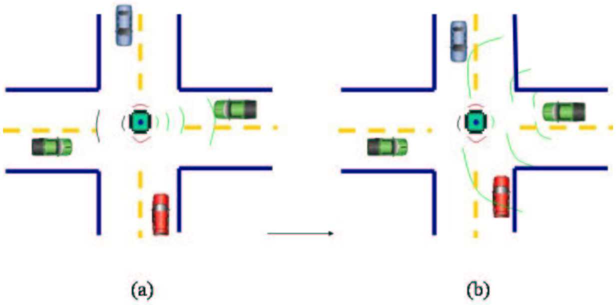

Fig. 1. The problem of wireless signal scattering

wireless traffic light kiosk sends out a "GREEN" signal for the vehicles travelling west, as in Fig. 1(a). The signal gets reflected by those vehicles and scattered to many directions. Both the north-bound and south-bound vehicles pick up the "GREEN" signal meant for the west-bound vehicles, as shown in Fig. 1(b). This kind of confusion will cause traffic issues rather than help solving them. We believe that solving this problem is the first step in developing a reliable wireless traffic signal system.

Our solution to this problem is a signalling protocol that encodes either a reference location and a direction, or two reference locations into each wireless traffic signal.

Next we present the design idea, a basic protocol, and show why the information we use is both necessary and sufficient. In section 3, we show how to augment the basic protocol to get application protocols such as intersection traffic light protocol and stop sign protocol. In section 4, we present the framework of our implementation. In section 5, we demonstrate the utility of the protocols by presenting an driver assistance application that utilizes the wireless traffic signals. Section 6 and 7 are discussion and conclusions respectively.

II. Basic Protocol

In order to let a vehicle differentiate all the broadcast wireless traffic signals in the air and recognize those for it, the following information is needed:

- the direction that the signal is in charge of.
- the heading direction of the vehicle.
- the location of the vehicle relative to the traffic signal.

The first two requirements are obvious. The following scenario shows why the third is just as important. Assume you are travelling north and approaching an intersection. You received a wireless intersection traffic signal. The signal contains a tag saying that, it is meant for north-bound vehicles and its state is GREEN but turning red shortly. You are happy and you pass the intersection. Immediately after you pass the intersection, you receive another signal for north-bound vehicle and it says "RED"! Upon receiving the signal you are travelling north but when you look around you see no traffic lights in the front. What should you do? You may laugh at the "dumb computer" and continue your trip. But to the software running inside the vehicle, information contained in the wireless signal is all what it "sees" about the traffic, assuming there is no other relevant sensing sources. Software acts according to rules, it might stop the vehicle or warn the driver. It has no notion of "just passed intersection" without additional information. But if the software is informed of the intersection location and its own location, and the signal explicitly says it is for north-bound vehicles before the intersection, then it is able to know that it can safely discard the signal because it is now north-bound after the intersection. From this example, one can see it is important to include some reference point information in the wireless signal besides the direction information to let users to know whether a signal is "from behind" or "from front". Fig. 2 shows four scenarios the signalling protocol has to be able to distinguish. One can see that a vehicle needs to know its own location and heading to make correct use of traffic signals. This is already made possible by the availability of locationing systems such as Global Positioning Systems (GPS). Henceforth, we assume a vehicle always has the knowledge of its own location and heading.

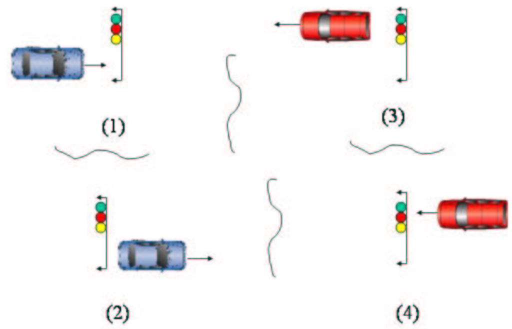

Fig. 2. Signal direction v.s. vehicle heading and location: four scenarios

Our basic wireless traffic light protocol requires each signal message to augment the type and state information with at least two location information.

type	state	s-location	r-location	other info

The first location (**s-location**) is the *source location*. Take traffic light, for instance, it can be the location of the traffic light module. This information can be manually set in a configuration file when a traffic light module is installed, or be dynamically obtained from a GPS receiver or other location sensor if the module contains one. The second location (**r-location**) is a *reference location*, that is used to indicate the direction that the signal is in charge of. This information has to be manually set when the module is installed. "Other info" can include the stop line distance to the source at the corresponding segment of the road, etc. Figure 3 is an example showing the the source loca-

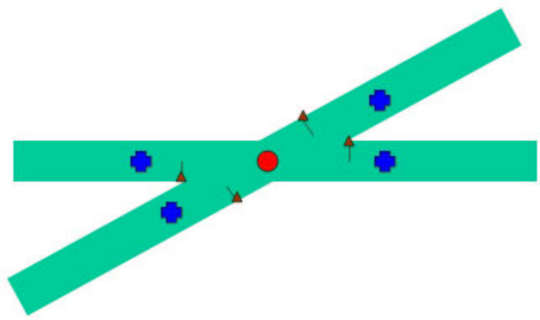

Fig. 3. Example: Reference locations in an angled intersection

tion (circle) and reference location (cross) for each way of an angled four-way intersection.

Let signal source location be (x_0, y_0), reference location be (x_1, y_1). We call $\vec{R_r} = (x_0 - x_1, y_0 - y_1)$ the *signal reference vector*. Let the vehicle location be (x, y), it heading is θ. The heading angle value can uniquely determine a *heading vector* $\vec{R_h}$. Finally, we call $\vec{R} = (x_0 - x, y_0 - y)$ *source-vehicle vector*.

Next we show that the question of whether a signal is for a specific vehicle or not can be answered from the relation between these three vectors: the signal reference vector, the vehicle heading vector and the source-vehicle vector. As shown in Figure 4, when the angle between the signal

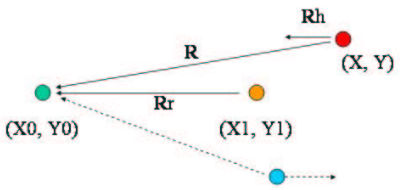

Fig. 4. Three vectors and their relation to signal-vehicle relevancy.

reference vector $\vec{R_r}$ and the source-vehicle vector $\vec{R}$ is small, we know the vehicle is in the area that the signal is guiding. If we also know the angle between the heading vector $\vec{R_h}$ and the reference vector $\vec{R_r}$ is very small, then we are sure that the vehicle is heading to the location of the signal source. The angle θ between two vectors $\vec{R}$ and $\vec{R_r}$ can be easily computed using the following formula:

$$\theta = asin(\frac{|\vec{R} \times \vec{R_r}|}{|\vec{R}|.|\vec{R_r}|}) \quad (1)$$

Likewise, the angle θ_h between two vectors $\vec{R_h}$ and $\vec{R_r}$ is

$$\theta_h = asin(\frac{|\vec{R_h} \times \vec{R_r}|}{|\vec{R_h}|.|\vec{R_r}|}) \quad (2)$$

Accordingly, the signal validity criterion is whether both of the following conditions hold:

$$|\theta| < \delta_1 \quad (3)$$

$$|\theta_h| < \delta_2 \quad (4)$$

Where thresholds δ_1 and δ_2 are protocol specific, i.e., their values depend on the scenario and reliability requirements of the corresponding traffic signalling system. The scenario specific protocols shall augment their basic protocol message with information about δ_1, some might also want to specify δ_2.

Next section we show how to extend the basic protocol for two typical traffic signal needs: stop sign and intersection traffic lights, in different scenarios, discuss how the corresponding thresholds shall be chosen.

III. Augmented Protocols

The basic signal protocol presented in the previous section lays a framework for constructing generic orientation-sensitive traffic signal messages. Practical protocols are expected not only to implement the basic signal requirements, but also to augment it with protocol-specific information.

Here we present two extended signalling protocols. One for intersection case, and another for stop sign case.

A. Intersection protocol

Improving the traffic safety in roadway intersections was our original goal that led us to pursue a wireless traffic signalling system. Once drivers are able to observe clearly traffic signal under low visibility conditions created by glare, heavy snow, fog etc., we expect related accidents will be reduced. Furthermore, we believe wireless intersection signalling is a problem that must be solved for the future automated transportation systems.

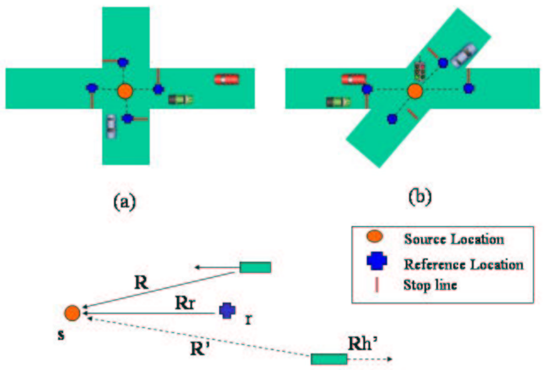

Fig. 5. Four-way intersection scenarios

Our intersection protocol defines a source location which is the center of the intersection, and a reference location at the stop line location for each segment of the road way connecting the intersection, as shown in Figure 5. Accordingly, the following information is contained in each protocol message:

4Way-Light	state	s-location	r-location	

δ_1	other info

where state can be red, yellow, green, left-turn green, etc. For a perfectly perpendicular intersection scenario as in Figure 5(a), δ_1 could be $\pi/2$. For an angled four-way intersection as in Figure 5(b), the acute angle of the intersection can be chosen for δ_1. We recommend to choose

3/4 or 1/2 of the acute angle as δ_1. This choice can avoid vehicles that deviate from their lanes on other road segment to misinterpret the signal. "other info" can contain information such as time-to-turn red, time-to-turn-green, etc, depending how sophisticated one wants the wireless signalling to be.

On the client side, once a vehicle pick up a signal, the following simple computation and logic is applied to filter out the irrelevant signals:

1. if message type is "4Way-Light", compute θ and θ_h as defined in equations 1 and 2.

2. if $\theta < \delta_1$ and $\theta_h < \pi/2$, pay attention to the state information in the message.

Furthermore, because the reference location is also the stop line location, vehicles are informed where their should stop when they are facing a red light (and no car is stopped in front of them).

B. Stop Sign Protocol

Stop signs are relatively cheap to deploy, and frequently used in small streets and country areas where installation of traffic lights are not as cost effective. Stop signs also have the advantage of traffic self-regulation as compared to traffic lights. For instance, in a four-way stop sign scenario, the first-come-first-go rule reduces maximum latency for each vehicle at the intersection to a minimum. While the cost issue of replacing stop signs for electronic systems still exists, but with the cost of electronics going down quickly and the need for auto-piloting of vehicles rising, there is a potential of electronic stop sign deployment in selected areas in the near future.

Fig. 6 shows two examples of one-way stop sign and how the source and reference location should be placed. The

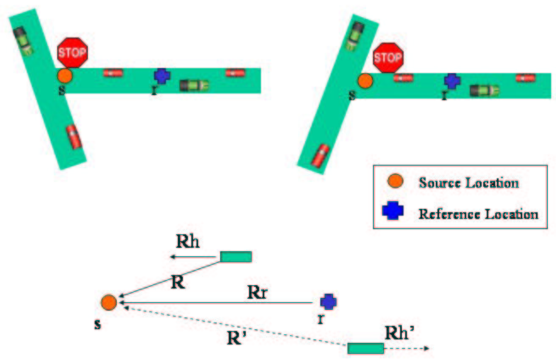

Fig. 6. One-way stop sign scenario

stop sign protocol message is of the following form:

Stop sign	s-location	r-location	δ_1

Note that the state information part is omitted, because stop sign protocol contains only a singleton state. δ_1 is the acute angle of the road intersection.

The client side logic is similar to that of the intersection case.

IV. Implementation

We have implemented the intersection protocol. Fig. 7 shows the major components and their relations in our traffic light Client-Server package. The traffic light controller periodically broadcasts traffic signal protocol messages. The traffic light monitor picks up the traffic light messages and and pass them to the related vehicle agents. The vehicle agents can differentiate the signals if they also have information about their location and heading, which are obtained from location and heading monitors.

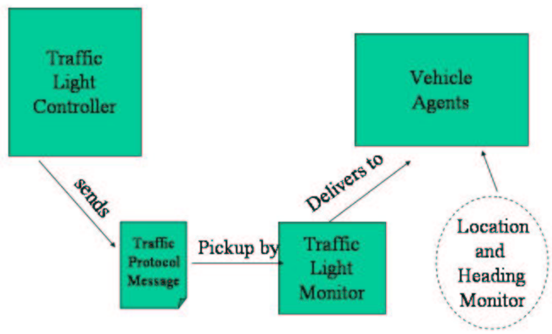

Fig. 7. Major components in the Traffic Light Client-Server package

The programming language used in our prototype implementation is Java. The following is the signature of the traffic protocol message:

```
package itss.protocols;

public class TrafficLightProtocolMessage {
    public int getType();
    public int getState();
    public Location getSourceLocation();
    public Location getReferenceLocation();
    public double getAngleThreshold();
}
```

The type constants such as traffic lights or stop sign are defined in an interface class

```
package itss.protocols;
public interface TrafficProtocolConstants{
    public static final int 4WAY_LIGHTS = 1;
    public static final int STOP_SIGN = 2;
}
```

The implementation is used in our intelligent traffic simulation system to demonstrate the feasibility of wireless traffic signals and how their introduction to augment existing traffic control will influence the characteristics of traffic, and to what extend it would help reduce the rate of accidents. Figure 8 is a snapshot of the simulation in an perpendicular four-way intersection.

V. Application Example: Red Light Alert Agent

Once reliable wireless traffic signals are available. They can be used for many purposes, ranging from driver assistance tools to automated vehicle applications.

In this section we present the design of a traffic signal alert system that will warn the driver of red-light signals if him/her has not reacted in time. As shown in Figure 9,

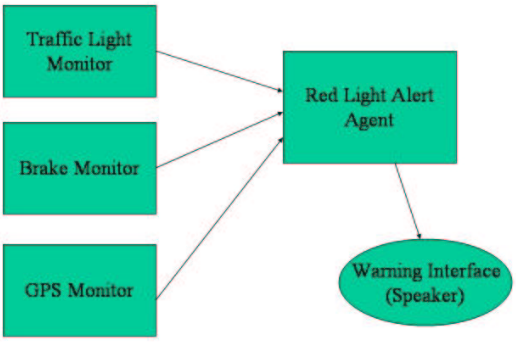

Fig. 9. Red-Light Alert System: Architecture and Data Flow

the red-light alert system contains for major components: a traffic light monitor, a brake monitor, a GPS monitor and a red-light alert agent. The GPS monitor is a wrapper around the GPS receiver. It constantly feeds current location and velocity information to both the traffic light monitor and the alert agent. The traffic light monitor picks up traffic signal messages, parses them, selects relevant ones using the location and velocity information provided by the GPS monitor as discussed in earlier sections. The red-light alert agent pulls information from the three monitors and decides if a warning needs to be issued given the information.

The warning/alert algorithm needs to strike a balance between early warnings and late warnings [3], [4], [5]. A conservative concern with safety tends to be biased on early warnings. For instance, when the warning system observes an impending danger to take place in 5 seconds without either human or machine intervention, a conservative algorithm tends to warn immediately. The reason is that a postponed warning may not leave enough time to reactions, and thus it is less safe. Yet, this conservative approach tends to give false warnings, as the situations may change within the 5 seconds, the drivers might have already noticed the situation and preparing actions. On the other hand, one should't postpone the warning too much. A warning occurs too late for the driver/system to act properly is not very useful either. We use the consideration of vehicle dynamics and human factors to help determine the appropriate time for issuing warnings.

Assume the vehicle is driving at the speed v to the intersection, and the maximum deceleration is a_{max}, then the stopping distance, i.e., the distance it takes for the vehicle to come to a full stop, is

$$d_{stop} = \frac{v^2}{2a_{max}}$$

Assume the average driver reaction time is t_r. The warning distance used in our red light alert agent is

$$d_{warning} = d_{stop} + vt_r + vt_a$$

where t_a is a parameter representing advanced warning time. The larger t_a is, the more conservative the agent is. The idea situation is set t_a to be zero. But due to the fact the location, velocity values are not always accurate, and the values are not continuously available (GPS receiver provides data at discrete times), a proper t_a (non-zero) needs to be chosen for a corresponding physical system. For our GPS-based locationing system, we use the following:

$$t_a = \frac{\Delta v}{a_{max}} + \Delta t_r + 2\frac{\sigma_d}{v} + t_p$$

where Δv is the uncertainty in speed estimation, Δt_r is the uncertainty in driver reaction time, σ_d is the standard deviation of the GPS location readings, and t_p is the period that traffic light signals are being broadcasted.

The red-light alert agent issues a warning if the following conditions are met:

1. the vehicle is facing a red light,
2. its current distance to the red light is smaller than its warning distance,
3. the driver has not taken action (press the brake),
4. a warning has not been issued for the same red light.

The corresponding alert algorithm is in Fig. 10

<u>Signal Algorithm</u>

LOOP1:
  LOOP2:
    1. Listen for traffic signal message
    2. On message arrival, get state, location1, location2
    3. **if** *heading to a red light*
    4.   **if** $d < d_{warning}$ and driver not braking
    5.   issue WARNING, goto(8)
    6.   **end if**
    7. **end if**
  END LOOP2
  8. Wait until pass the intersection.
END LOOP2

Fig. 10. Red Light Warning Algorithm

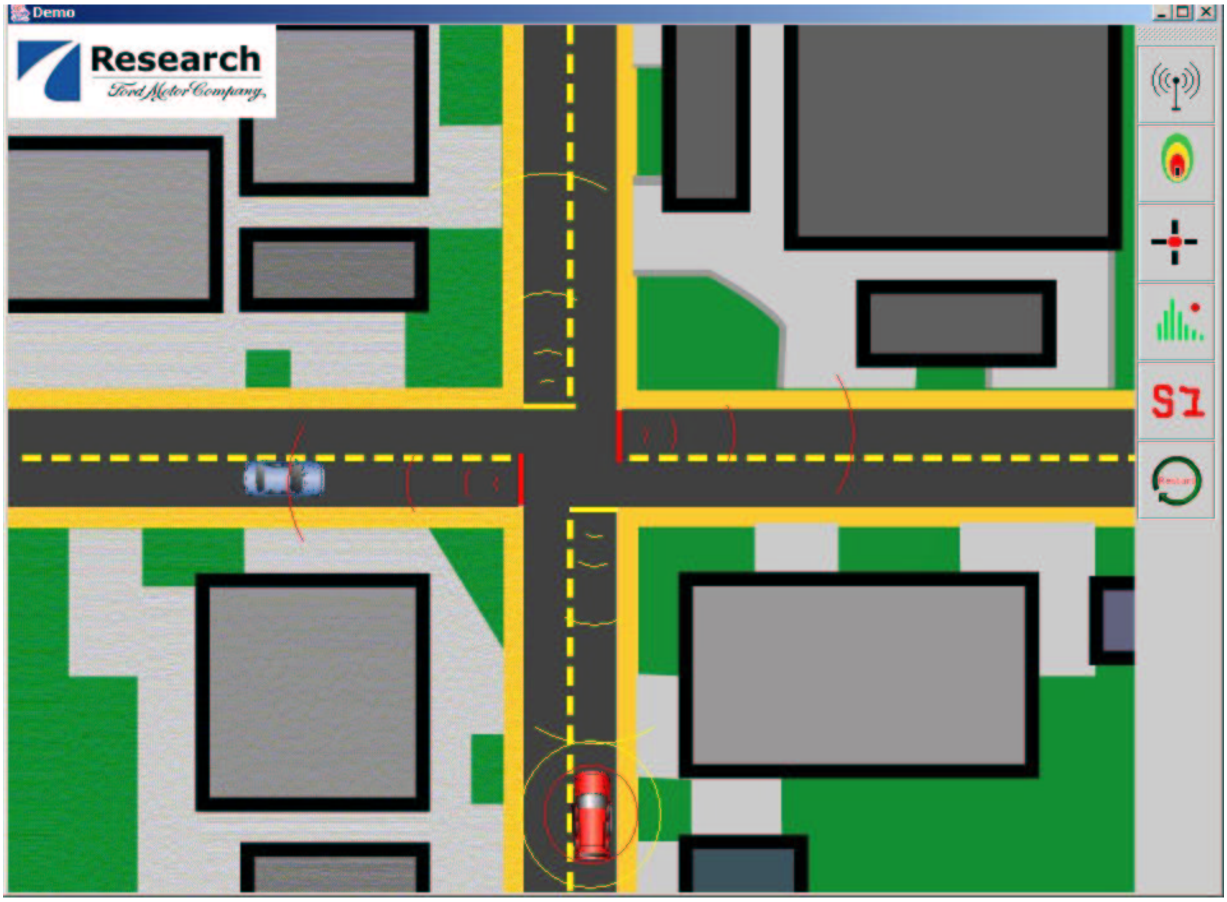

Fig. 8. Intersection Traffic Light Demo

VI. Discussion

We have presented key elements in our traffic signal protocols. The introduction of the source location and reference location enables simple encoding of direction and stop line information in omnidirectional wireless signals. The introduction of threshold δ eliminates potential confusions in angled intersections. So far, we assumed that the vehicles have accurate location and heading information with respect to the locations set in the traffic control signal. The validity of this assumption depends of the source that provides these information. For instance, if the information is provided by GPS, then there is potential drift of location readings because changes in atmosphere conditions. When this drifting occurs, the preset locations in the traffic controller are relatively "dislocated". This will cause misjudgement from the vehicle side. To avoid this problem, the controller should always be equipped with a GPS receiver and dynamically re-adjust the source and reference locations according to most current readings of the GPS data. On the other hand, if the location information is provided by some preset devices embedded on the roadway, then drift is unlikely and there is no need for dynamic re-adjustment.

In principle, the wireless traffic controller should broadcast the traffic control information as frequent as possible. The more frequent it is, the more "aware" the vehicles are. But if the broadcast frequency is too high, it also runs the risk of overloading the networks or overloading the computation power in each vehicle. A delicate balance should be taken in practice. In our simulation, the frequency is ten Hertz, and it works well for vehicle speed under 40 miles/hour.

Obviously, the wireless signal shall be synchronized with the regular signal when used as an augmentation. We recommended a slightly advance signalling of wireless signals, due to the consideration of the processing delay of the wireless signals as compared to human visual capability. How far ahead should the wireless signal be is a question to be answered by simulation and in practice.

VII. Conclusion

Electronic traffic signal has the advantage of being easily visible to machines. It is expected to augment the traditional traffic light system in future intelligent transportation environments, where intelligent vehicles interact with each other and with traffic systems and give informed advisories to drivers. We identified benefits of wireless signalling and the potential problem of omnidirectional property of wireless signals, and discussed how it should be handled using appropriate protocol level information. We presented a simple and reliable protocol for electronic traffic signalling systems, and showed how to extend it for different purposes. The protocol enables recipient vehicles to robustly differentiate the signal's responsible directions despite of potential threats caused by reflections. We presented a red-light-alert driver assistance system that takes advantage of the electronic traffic signal system. We also addressed potential inconsistency threats caused by the drift GPS, and discussed means to handle them. This is a step in our research in building a reliable intelligent transportation system. We believe this work will provide some guidelines for future efforts in ITS work.

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