GPS based Vehicular Collision Warning System using IEEE 802.15.4 MAC/PHY Standard

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***Abstract*—Detection of other vehicles in the vicinity of a moving vehicle is of primary importance to help the driver safely negotiate acceleration, deceleration and parking. In these situations the vehicle must acquire its positional knowledge with respect to others and be able to identify a possible collision. This paper introduces an active alarming system for predicting a collision between two or more vehicles using GPS and IEEE 802.15.4 MAC/PHY specification compatible system on chip (SOC). We develop a generic estimation mechanism for the safety coordinates of a vehicle based on its orientation, size, current speed, acceleration and its braking potential. Such safety coordinates are communicated among all vehicles in proximity and is used to determine overlaps thus detecting a possible collision. The IEEE 802.15.4 standard is designed for low rate wireless personal area networks and we investigate its applicability in a VANET through two series of tests. Firstly, we simulate a scenario of upto 10 vehicles in proximity and test the practically achievable throughput using commercially available SOCs. This gives an estimate of the best average latency the standard can support. We also simulate our system in NS2 and study the packet loss as a function of periodicity of packet transmission, the number of nodes and the mode of data transmission.**

Keywords- GPS; IEEE 802.15.4; Anti-collision device;

I. INTRODUCTION

Invention of automobiles was one of the greatest commercial achievements of mankind in the past century and has contributed in many ways to the growth of a nation. However, we can not ignore the fact that thousands of people lose their life or suffer life changing accidents due to vehicular collisions every year. Research in vehicular anti-collision systems has received widespread attention with active work being carried out for over four decades. Causalities in traffic accidents are mainly caused by collision between vehicles due to the inability of the drivers to gauge the perimeter of their vehicles. This is particularly accentuated in large vehicles like trucks where there are many blind spots.

Recent efforts have been made at developing a cooperative anti-collision system where an ad-hoc wireless communication network is formed among vehicles in proximity. Coupled with positional data from a Global Positioning System (GPS), these devices are relatively cheap to realize and holds the potential for use of allied applications like centralized tracking of vehicles, traffic management and stricter regulation of vehicular speed. A vehicle collision avoidance system based on cooperative wireless communication and GPS can eliminate the drawbacks of the optical based technology even under high speeds or under near-zero visibility [16].

In this paper we introduce an active alarming system for moving vehicles using Global Positioning System (GPS) and a wireless communication module adhering to the IEEE 802.15.4 Medium Access Layer (MAC) and Physical (PHY) specification [8] operating on the license free Industrial-Scientific-Medical (ISM) band of 2.4 GHz. To the best of the authors' knowledge, this is the first work developing a vehicular anti-collision system on IEEE 802.15.4.

The motivation for our work stems from the authors' visit to an open cast mine of India. Here, dumpers of huge proportions, ferry cargo from the mining to the dumping area. The visibility when inside the cabin of the dumper is next to minimal. Blind spots exist at the rear and the sides. Further, the dumpers are around twenty feet in height and its difficult gauge the distance of obstacles on the ground. Collisions are therefore an everyday affair with serious accidents leading to human casualties. A collision between two dumpers leads to losses both due to the repairs needed and the opportunity cost by their unavailability till the repairs are completed. The size of the dumpers also reduces the applicability of conventional collision warning systems like infrared and optical based since the number of devices needed to cover the entire perimeter of the dumper is large. The dumpers operate in an open area where there are few obstacles. Direct reception from satellites is possible thus allowing the use of GPS. A dumper is pictorially shown below.

Figure 1: A dumper in an open cast mine.

We develop a collision warning system for use in such dumpers where an important aspect is the generation of the perimeter of the truck. Our system, however, is generic enough for use in everyday vehicular traffic where conditions similar to an open cast mine exists, like that in a highway or open crossroads. Proceeding further, our focus lies on dumpers in an open cast mine, unless otherwise stated. The active alarming system uses GPS to collect the current *latitude* and *longitude* position of the moving vehicle along with the *azimuth* and *speed*. Based on these values the system calculates the rectangular perimeter of the vehicle represented by *four* safety-coordinates. The four coordinates are then transmitted to neighboring vehicles using the IEEE 802.15.4 standard. Simultaneously, checks are made to ensure the rectangular perimeter of an incoming packet, which corresponds to other vehicles, does not overlap with its own perimeter.

The paper is structured as follows. In section II we present the related work and provide the motivation for our work in this paper. Section III develops the system model and section IV provides the performance of the GPS module and the IEEE 802.15.4 communication module. We provide the scope for further work and conclude in section V.

II. RELATED WORK

Vehicular collision warning systems (CWS) are traditionally classified into two categories. Initial work focused on systems where a vehicle would gauge obstacles in its path through the use of cameras, radars, acoustic systems, etc [6] where each vehicle is autonomous and is capable of detecting obstacles, even of heterogeneous types. However, such devices are cost prohibitive Further, research has progressed to identify potential collisions between moving vehicles meeting at a cross road. In such systems, Inter Vehicular Communication is necessitated between vehicles that are not in the line of sight. Inter vehicular communication has received wide spread attention with the near ubiquitous nature of 802.11 [13]. A collision warning system based on inter vehicular communication involves the broadcast of the vehicle coordinates and other information like speed and direction on a wireless channel. These systems are thus known as cooperative CWS (CCWS) [6]. A CCWS cannot identify heterogeneous obstacles, however, based on the propagation property of the wireless system they can see through buildings to reduce blind spots. Numerous studies have been made on CCWS where GPS data including speed and direction are transmitted to other vehicles using 802.11 [12][13].

A common assumption of such systems is the homogeneity of vehicles, where the dimension of each vehicle does not feature in the determination of collision boundaries. Further, the future position of a vehicle is estimated by the vehicle receiving the broadcasted information. In this paper, we deviate from the conventional CCWS in three aspects. Firstly, every vehicle based on its direction of travel computes, in longitude and latitude, the four corners of its safety zone as shown in figure 2. Thus vehicles of varying profiles are integrated. Secondly, the safety zone is made a function of the speed, acceleration and the braking power of the vehicle. For example, a vehicle traveling at high speeds would require a longer braking distance to successfully avoid a collision. This is made possible by warning the user in advance by having a longer *front (F)*. Similar dimensions can be obtained for a vehicle whose stopping power is compromised. Thirdly, we utilize the newly ratified 802.15.4 standard for inter vehicular communication. We use commercial off-the-shelf GPS devices which have a precision of 7 meters. We do not explore DGPS (Differential GPS) systems for its cost and non availability in most parts of India. The IEEE 802.15.4 standard was specifically designed for low cost systems and the modules are of a small form factor, fairly cheap and easy to program. They are able to provide a line of sight range of around a kilometer and a non-line of sight of around 100 meters. In comparison with 802.11, the memory requirement of 802.15.4 is small, easily implementable and power requirement is low. The data rates supported are a theoretical maximum of 250 kbps (kilo bits per second). We seek to investigate the applicability of IEEE 802.15.4 for collision warning systems.

III. SYSTEM MODEL

Of the various formats available from the GPS receiver we use the GPRMC format, also known as the *recommended minimum* [7]. The length of the GPRMC sentence is around 80 ASCII characters and is updated every second.

A. *Calculation of vehicle's safety zone coordinates*

Figure 2 shows the calculation of the four safety-coordinates of a vehicle. The front (*F*) and back (*L*) and width *(W)* would be different for vehicles of different sizes. Such generic mechanisms is particularly applicable in city traffic where cars would require a smaller safety clearance than a truck.

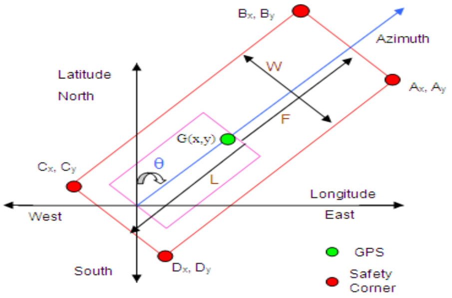


Figure 2: Schematic diagram for calculating the *four* safety-coordinate of a vehicle.

It is assumed that the GPS receiver is placed at the middle of the sideways safety clearance *(W/2)*. The GPS coordinates are received at the point *G (x, y)*. Let *F* = Front safety distance of the vehicle from G, *L* = Back safety distance of the vehicle from G, *W* = Width of the safety clearance of the vehicle side wise, θ = Azimuth angle in degree. The four coordinates are then calculated as:

$$A_x = x + F \sin\theta + \frac{W}{2}\cos\theta \quad (1)$$

$$A_y = y + F \cos\theta - \frac{W}{2}\sin\theta \quad (2)$$

$$B_x = x + F \sin\theta - \frac{W}{2}\cos\theta \quad (3)$$

$$B_y = y + F \cos\theta + \frac{W}{2}\sin\theta \quad (4)$$

$$C_x = x - L \sin\theta - \frac{W}{2}\cos\theta \quad (5)$$

$$C_y = y - L \cos\theta + \frac{W}{2}\sin\theta \quad (6)$$

$$D_x = x - L \sin\theta + \frac{W}{2}\cos\theta \quad (7)$$

$$D_y = y - L \cos\theta - \frac{W}{2}\sin\theta \quad (8)$$

The different dimensions are incorporated in the values of L and W. The speed and the braking power of a vehicle are included in different values for *F*.

B. *Calculation of front safety distance: F*

The calculation of the safety distance *F*, is made taking into account the current speed, acceleration and the braking power of the vehicle. Also included in the calculation is the human reaction time (which we have ignored in our implementation). which is defined as the amount of time taken on average to apply the brakes once an indication is provided. We make an assumption in the calculation that the brakes are applied at its maximum potential. Denote *P* as the current location of the vehicle, *u* as its current speed and *a* as its current acceleration. Let t_h be the human reaction time and the retardation due to the brakes is denoted as B_r.

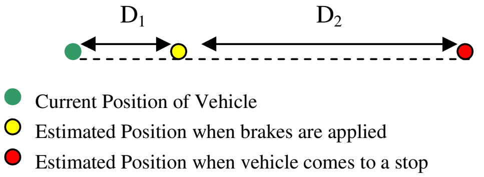


Figure 3: Schematic diagram of the final position of the vehicle (in red) with respect to its initial speed and acceleration.

Then, if T_{stop} is the time the vehicle takes to stop, the sum of D_1 and D_2, to obtain F, can be calculated as shown below.

$$T_{stop} = \frac{u + at_h}{B_r} \quad (9)$$

$$D_1 = ut_h + \frac{1}{2}at_h^2 \quad (10)$$

$$D_2 = V_1 T_{stop} + \frac{1}{2}B_r (T_{stop})^2 \quad (11)$$

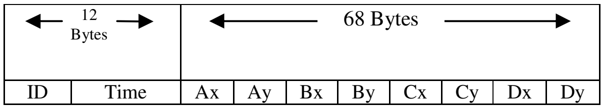
where $$V_1 = u + at_h \quad (12)$$

$$F = D_1 + D_2 = ut_h + \frac{1}{2}at_h^2 + \frac{3}{2}\frac{(u + at_h)^2}{B_r} \quad (13)$$

C. *Transmission of safety coordinates*

We build a packet with the calculated coordinates and transmit on the 2.4 GHz ISM band using the 802.15.4 standard. The packet structure is as in figure 4. Each communication device is pre-burned with a 16 bit unique address that forms the short address (as defined in the standard) and represents a vehicle. The time field is obtained from the GPS reading and is transmitted in ASCII in the format '*ddmmhhmmss*' corresponding to the date, month, hour, minutes and seconds and accounts for 10 bytes. The Latitude is made up of 9 bytes and is of the form yyyy.yyyy while the longitude is of the form xxxx.xxx and thus is transmitted as a 8 byte ASCII value. The payload then comes to 68 (9 * 4 + 8 * 4) bytes for the four coordinates. The total payload of 80 bytes fits with the IEEE 802.15.4 standard well.

The generated packet needs to be transmitted at periodic intervals to all vehicles in proximity and we need to design this periodicity. We also need to decide on the type of data transmission viz. a broadcast or an unicast. We configure the 802.15.4 in a non beacon enabled mode. Every device is pre-burned with a unique 16 bit address and thus there is no association and assignment of address (as supported in 802.15.4). The data packets are sent only to a device's neighbours and thus there is no routing required. A broadcast packet transmission would suffice with all devices being a Reduced Functional Device (RFD). However, for unicast, all devices have to be configured as a Full Functional Device (FFD) with the MAC told to respond to beacon requests (from an Active Channel Scan).



ID	Time	Ax	Ay	Bx	By	Cx	Cy	Dx	Dy

Figure 4: Packet structure with the coordinates of the safety zone. This packet is transmitted periodically by every vehicle.

The design of the minimum average periodicity is made theoretically making the following assumptions. Given *N* vehicles in proximity, there exists an imaginary process *god*, which has complete information of the topology and the presence of vehicles. It gives equal and unique time slots to each device for its transmission. This communication between *god* and the devices does not consume time. This guaranteed time slots ensures no packet collisions. We assume there are no latencies in the IEEE 802.15.4 protocol. Specifically, the latencies due to the *random backoff* [9] of the CSMA-CA mechanism before sensing the channel is assumed to be non-existant. The *aTurnaroundTime*, which denotes the time a device waits before switching from transmission to reception and vice-versa, is assumed to be zero. We also assume the channel is lossless. We calculate the minimum possible latency under such conditions. This gives an estimate of the minimum periodicity achievable. Further, in our practical tests using commercially available 802.15.4 communication chips, we determine the throughput achievable. This bandwidth is what is available to the devices, taking into account collisions, transmission retries and time latencies. Thus, applying our periodicity formulation with the practical throughput, we can obtain the best practical periodicity achievable for data transmission in a realistic, yet simple way.

C.1 Broadcast Transmission

In broadcast, a device transmits its data packet once the channel is sensed clear. There is no MAC level ACK (acknowledgement). Denoting T_{pkt} as the time needed to send or receive the payload of 80 bytes we can formulate the total time a device is busy, T_{busy_b}, as:

$$T_{busy\_b} = T_{pkt} + (N-1)(T_{pkt}) \quad (14)$$

The time spent by the microcontroller unit (MCU), processing the received packet and sounding an alarm if needed, can be ignored since these functions are done in parallel while the RF (radio frequency) unit is receiving the next packet.

C.2 Unicast Transmission

In Unicast, a device needs to first determine how many other devices are in its range. This is done by performing an 802.15.4 MAC primitive, ACTIVE_SCAN of the channel. A device performing an active scan sends a beacon request which is of 8 bytes in size. Upon receipt of a beacon request, a device responds with a beacon. We configure the beacon payload to zero. The size of the beacon frame then equals 13 bytes (GTS field and Pending Address field are of 1 byte each). Further, we assume MAC level ACK is enabled. The ACK packet is of 5 bytes in length. Note, all lengths mentioned are at the MAC layer. In addition to the variables defined above, let T_{ack} be the time to send or receive the ACK. Let T_{beacon} and $T_{beaconReq}$ be the time to send and receive a beacon (for ACTIVE SCAN).

$$\begin{aligned} T_{busy\_u} &= T_{beacon\,Req} + (N-1)T_{beacon} + (N-1)(T_{pkt} + T_{ack}) \\ &\quad + (N-1)(T_{beacon\,Req} + T_{beacon} + T_{pkt} + T_{ack}) \end{aligned} \qquad (15)$$

The total time has been derived as follows. Initially, the device sends a beacon request and receives the beacon from all the other devices. This corresponds to the first two fields. Subsequently, the device sends the packet with the GPS coordinates to all devices individually. It receives an ACK from each of them. Similarly, it receives the beacon request from the other devices and responds to them. It also receives the coordinate packets from all the other devices and sends an ACK to each one of them.

The PHY layer header is 6 bytes and the MAC layer header and trailer accounts for 9 bytes. Assuming a data rate of 250 kbps at the physical layer, and N=10, we attain T_{busy_b} as 30.4 ms and T_{busy_u} as 76.48 ms. These times correspond to the theoretically achievable best average interval. We made a test with the commercially available SOCs to obtain the practical throughput (The results are shown in section IV). The practical throughput encompasses packet collisions, transmission errors and backoff latencies. In such settings, we obtained a throughput of 150 kbps with 9 transmitters. Plugging in this throughput, we obtain T_{busy_b} = 50.66 ms and T_{busy_u} = 127.5 ms. These times represent the best practically achievable average transmission interval. The packet transmission interval rate is fairly small and thus the data rates supported by IEEE 802.15.4 suffice a single hop transmission as in this application.

D. Determination of overlapping safety zones

The determination of the overlap between two perimeters is simplified by working on the coordinates of the four safety corners, thus reducing the complexity from an area (O(n2)) to an edge (O(n)). We focus on two possibilities – either vehicle A's coordinate(s) is inside the perimeter of vehicle B, or the other way around. We ignore the case when the areas are overlapping without any safety coordinate being in the perimeter of the other. This cannot happen without the coordinate having been inside the perimeter while the vehicle moves. Referring to figure 5, vehicle A would sound the alarm since its upper right coordinate is inside the perimeter of vehicle B. Vehicle C would buzz since the coordinate of B is inside its perimeter. Similarly vehicle A sounds the alarm.

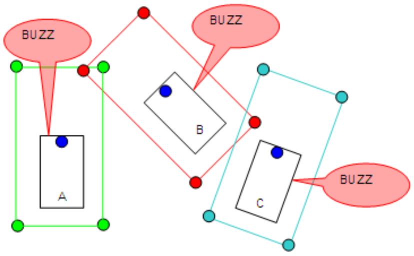


Figure 5: Schematic diagram for alarm generation in vehicles with overlapping safety zones

We use the standard and well known algorithm to determine if a coordinate is within another perimeter. A point *P (x, y)* is inside the convex polygon if it is to the left of every edge while traversing the edges counterclockwise. If *A*(x_1, y_1) and *B*(x_2, y_2) be the end endpoints of a directed line segment from A to B, then a point *P(x, y)* will be to the left of the line segment if the expression holds true:

$$c = (x_2-x_1)\,(y-y_1) - (y_2-y_1)\,(x-x_1) > 0 \qquad (16)$$

IV. SYSTEM PERFORMANCE

The hardware design of the collision warning system is depicted in Figure 6. The system consists of the following components: one 9 volt power supply (sourced from the vehicle battery), four LED indicators, a buzzer, a MaxStream XBee PRO/ Chipcon CC 2430 SOC with integrated RF transceiver housed inside the 'MAX Box'. A 3 volt supply is derived from the battery to power the SOC module. A single GPS receiver is driven by a 5 volt power supply through the same battery and a serial interface from the GPS to the SOC is made. The complete module is made compact with ports available for power supply and extension cables to house the GPS module on the outer periphery of the vehicle.

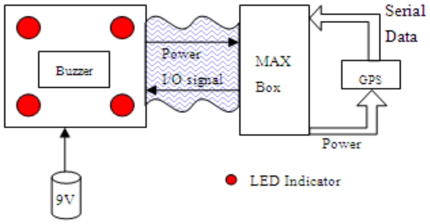


Figure 6: Hardware design diagram for the anti-collision system

A. Performance of the GPS modules

There are several limitations [15] of using readily available commercial GPS receivers like multiple reflections off buildings and other environmental factors. An imprecise system clock can lead to errors as well. The module in our implementation documented an accuracy of 5 to 7 meters. In our collision warning system, the GPS modules of neighboring vehicles are in close proximity (and there is no multi hop data transmission). We made tests of the GPS module in an open area with no buildings or trees in close range. We thus expected reasonable accuracy of the devices since there would be a good chance of the modules picking the same satellites for their calculations and multi-path reception is minimized in an open area. The only source of error would be the inaccuracies of the system clock.

We show below the result of a test made. Two vehicles are moved towards each other. The vehicles were aligned in such a way as to expect the latitudes to remain constant when the vehicles move with changes only in the longitude. The plot of the safety zones as the vehicles move is shown in figure 7. The initial positions of the vehicles are shown as *POS 1*. The intermediate locations are *POS 2* and the final positions are shown as *POS 3*. The relative positional error turned out to be 10m which is half the width (*W*) of the safety zone.

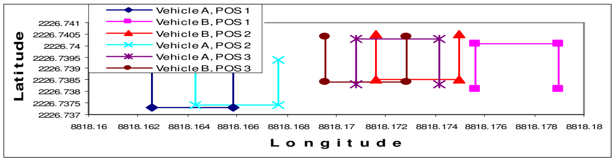


Figure 7: Plot of the safety coordinates of two vehicles moving towards each other. The vehicles were aligned to expect a constant latitude reading and only changes in the longitude when the vehicles moved

Figure 7 shows that the relative error is quite significant when we wish to achieve accuracy in the range of 2 – 5 meters. Vehicle B shows constant latitude reading as expected, however vehicle A is error prone.

B. *Performance of 802.15.4 for inter vehicular communication*

The calculated safety-coordinates of a vehicle needs to be communicated reliably and as quickly as possible to all vehicles in vicinity. Ideally, once the safety-coordinates are calculated every vehicle must be aware of it instantly. A communication delay induces an error in the calculated coordinates due to the motion of the vehicle. We thus seek to minimize the time period between subsequent data transmissions. We made two series of tests. Initially the practically achievable throughput over a single hop using the commercially available devices was determined. We also developed our application in ns-2 [14] and made a study of the packet loss as a function of the periodicity, number of devices and the transmission type.

The practical measurements were made for two SOCs – the MaxStream XBee PRO [11] and the Chipcon CC2430 [4]. The former advertises an outdoor range of a kilometer and the latter of 500m. The throughput measurements were made by having a single receiver and multiple transmitters ranging from one to nine. This simulates the number of vehicles that can be in communication proximity. The data payload was fixed at 80 bytes representing the safety-coordinates. The devices were placed such that every device is in the range of all other devices. The throughput measured for the SOCs are shown in figure 9. CC2430 degrades much better when compared to XBee. Note that the random backoffs of the CSMA mechanism and the turnaround time (as explained in section III) allow for a higher throughput when the number of devices increase. This is accordingly seen in figure 9.

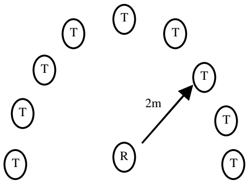


Figure 8: The experimental setup for the practical throughput measurement. T: Transmitter, R: Receiver. All devices are in range of each other.

The throughput shown is at the physical layer taking into account the header (15 bytes) and the ACK (11 bytes). Note that the sizes of these headers are at the physical layer. The throughput is found to stabilize at 9 devices at 150 kbps for CC2430 and 80kbps for XBee PRO.

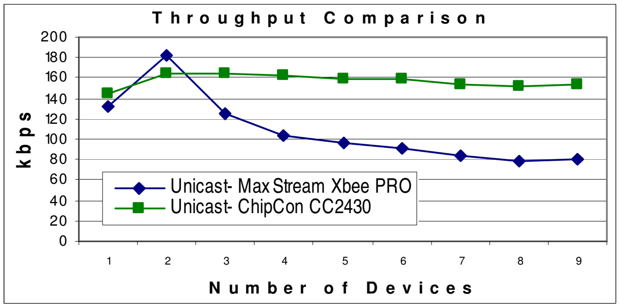


Figure 9: Comparison between the throughputs of the two SOCs

The discrepancy between the devices in the achieved throughput, we believe, is due to the higher transmission power of the XBee thus producing a larger interference. However, we need to delve deeper into the apparent performance difference.

To measure the performance of the system in a realistic scenario, we implemented our scheme in both broadcast and unicast modes in NS2. The area of the simulation was set at 50 x 50 m and the node positions were made random such that every node is in the range of every other. The total duration of each simulation was 60 seconds. Changes were made to the ns-2 simulator to make use of the data primitive - MCPS_DATA_REQUEST. We varied the periodicity of the packet transmission and recorded the total packets received as a function of the total packets that were to be sent in the simulation window.

The performance graphs are shown in figure 10. The broadcast transmission shows a 100% packet arrival with a 1 second periodicity and degrades with increase in the frequency of packet transmission. Interestingly, unicast transmission shows a very meager packet arrival (figure 10(b)) and degrades rapidly with the number of nodes in the system. Upon investigation it was found that most losses happen during the beacon request phase, where the broadcast for beacons was lost at least by 1 device in most occasions. A plot of the system performance with direct unicast, i.e without making a channel scan shows this phenomenon till the number of devices are around 5 (figure 10(c)). Thereafter, a huge drop in packet arrival is noticed. We thus conclude from the performance tests that a 1s period with broadcast is fairly reliable.

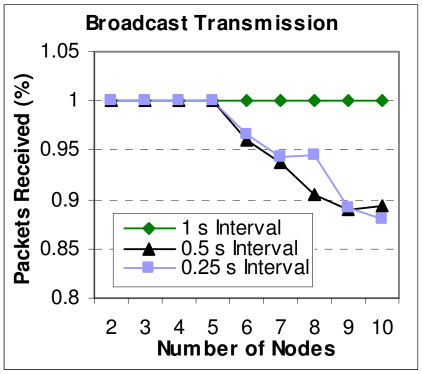


Figure 10(a)

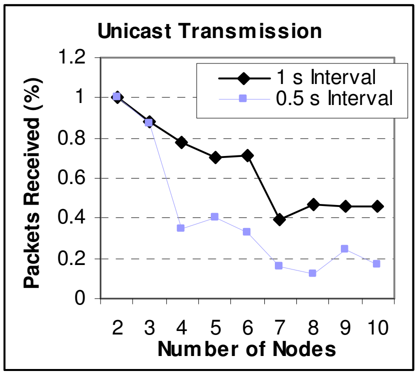


Figure 10(b)

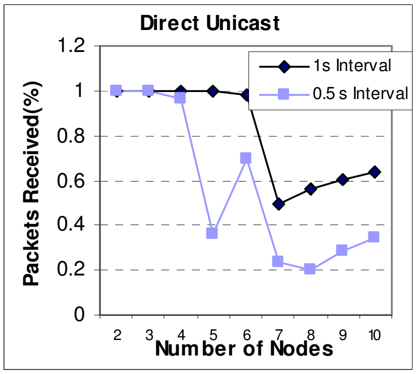


Figure 10(c)

The result of the unicast simulation throws up an interesting challenge. Broadcast, on one hand shows good packet arrival rate, but it inherently has no mechanisms for reliability. Unicast, on the other hand supports reliability to some extent through the MAC level acknowledgements. However, we find its performance is far from satisfactory. This is due to the overhead of multiple beacon request/response. Thus there is a need to develop a unique scheme that has a low overhead, similar to a broadcast while ensuring some minimal reliability like the MAC layer acknowledgements in a unicast.

V. CONCLUSION

In this paper we have proposed and analyzed the effectiveness of an active anti-collision alarming system for vehicles using IEEE 802.15.4 MAC/PHY specification, where each anti-collision system installed in a particular vehicle transmits its positional information and simultaneously listens to similar information from other vehicles in proximity. We have developed a generic estimator for the safety-coordinates and shown the applicability of IEEE 802.15.4. The results show a better performance of the CC2430 SOC in the practical test. In our ns-2 simulation, we find a surprisingly poor performance of the unicast mode of transmission over broadcast. Taking these tests forward, we would like to develop a better scheme for unicast transmissions where certain information can be piggy backed on other packets. For example, a scheme where the number of devices in range is exchanged among vehicles through the unicast packets can be explored. The adaptability, low cost and easy programmability of the IEEE 802.15.4 standard gives us impetus to enhance the application in wireless vehicular networks.

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