Power Efficient Vehicular Ad Hoc Networks

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***Abstract*—Inter-vehicular communication is a growing platform for improving roadway safety. The highly mobile nature of Vehicle to Vehicle communications causes rapid changes in network topologies and propagation conditions. Since the advent of Vehicular Ad-Hoc Networks (VANETs), over fifty routing protocols with attendant topologies have been proposed. Despite these protocols' merits, many of them are not optimized for power management and frequency reuse. Our approach utilizes the one dimensional dynamic of divided highways to simplify the routing problem and reduce energy consumption. Since each car is aware of only two types of connections, up-road and down-road, we can form low power, line of sight links between adjacent vehicles. We also utilize a fuzzy logic algorithm that predicts the location of up-road cars to reduce interference from request for link signals. Once these links have been established, up-road vehicles send data down-road for a length of time based on the relative speed of the two vehicles. After this time period has expired the down-road vehicle must request additional information, restarting the timer. Data sent through the network will include information on up-road vehicles, and when required, messages such as accident notifications, alerts, and traffic warnings. Through simulation, we show that our approach to VANETs maintains its update frequency despite bumper to bumper traffic and uses two to five orders of magnitude less power than an IEEE 802.11 network with clustering and 1 mW transmit power. Overall, the network performs well and is a viable improvement to the standard.**

I. INTRODUCTION

Improving the safety and comfort of transportation in major traffic areas has become a prevalent matter in the study of telecommunications. Research in this field focuses on Vehicular Ad-hoc Networks (VANETs), an adaptation of Mobile Ad-hoc Networks for exchanging data between vehicles and roadside infrastructure [1]. This form of communication is a routine for transferring information about the road between distant vehicles by having them communicate with each other directly. Vehicle to Vehicle (V2V) communications play a major role in making safety and comfort possible.

The primary challenges associated with these types of spontaneous networks are rapidly changing topologies and propagation conditions. The topology of a network of vehicles is the pattern formed by the physical location of each node in the network. Propagation conditions are the electromagnetic properties of the media between a pair of transmit and receive antennas. Careful topology design can help a VANET avoid problems such as: reduced transmission capacity, increased end-to-end packet delays, and possible node failures. Data transmission can be optimized by predicting the propagation conditions based on the designed topology and known properties of the road [1].

Various routing protocols and topologies have been established in previous research to mitigate these problems. Despite their differences, a common element they share is a reliance on wireless multi-hop communication. Wireless multi-hop communication is the idea that information should pass from one node to another over wireless links until it has traveled from its source to its stated destination [2]. Managing the power used to maintain a wireless link between two nodes in a VANET is not significantly different from the methods used in traditional wireless networks. However, the particular challenges of VANETs must be considered when setting up these links. Since the topology of a VANET changes rapidly, new links must be formed quickly.

This paper proposes a VANET topology and routing protocol based on dimensional reduction, clustering, and minimal length for line of sight connections. This is enhanced by a method for reducing link formation power consumption with a fuzzy logic algorithm, for predicting vehicle locations, and a link maintenance algorithm, for predicting link lifetimes based on the dynamics of the transmitting and receiving vehicles.

The rest of the paper is organized as follows. Section II gives background information on VANET routing protocols and explains how a band plan are used for wireless communication systems. Section III explains our system's: network topology, band plan, fuzzy link formation algorithm, link maintenance algorithm, and message formatting. The simulation's results are then given in Section IV. Finally, we conclude in Section V.

II. BACKGROUND

Integrating wireless communications into transportation has been of great interest to many researchers due to its potential for improving current transportation systems. VANETs have been designed to relay information such as: hazard warnings, vehicle conditions, and traffic data between vehicles and roadside infrastructure [3]. Despite its recent popularity, there is still much to study about these systems. VANETs need to be able to share information between cars while taking into account many obstructions including different vehicle speeds and the electromagnetic properties of the physical link between antennas. VANETs have been studied recently by many researchers but there are still several areas of active exploration [1].

Different routing protocols have been proposed to solve the challenges in the V2V VANET communications. These approaches can be classified under six categories: topology, position, cluster, geocast, multicast and broadcast based routing protocols. Topology based protocols focus on sending information in the network through packet forwarding- sending packets through nodes until all the nodes in the topology have the information. Positioned based protocols use the data from a GPS to make routing decisions rather than relying on link data; information is forwarded based on location instead of link connection. Cluster based routing protocols use VANETs in a hierarchical manner; vehicles close to each other form clusters and share information from a main source. Each cluster has a head node that links with other clusters' head nodes to form the overall network. Geocast based routing is similar to positioned based routing but adds the concept of a zone of relevance (ZOR), or area in which each vehicle cares about the state of the road. Multicast routing is an offshoot of geocast routing that adapts multicast protocols from fixed networks to VANETs. This type of protocol focuses on sending packets of information from one or many nodes to the entire network. Finally, broadcast routing protocols focus on disseminating information by flooding, or broadcasting information from each node to every node it is connected to. This process is repeated by every node receiving the information [1].

Another important aspect to look at when forming topologies with V2V communications is a network's channel definitions or band plan. In the United States, the Federal Communications Commission (FCC) allocated 75 MHz of spectrum from 5.850 to 5.925 GHz for use by an Intelligent Transportation System (ITS) in 1999 [4]. In 2004 the FCC specified seven 10 MHz channels with a 5 MHz guard band on the lower end within the previously allocated spectrum [5]. Due to this mandate, researchers have converged on this band plan.

III. Methodologies

A. Network Topology

The central challenge of designing a VANET is creating a topology that can function in a highly dynamic environment. In order to represent an environment that has constantly changing situations, we refer to an interstate highway. This allows us to consider a node with different surroundings and its interactions with other nodes. We use the road's geometry to simplify the standard model of a planar network into a single dimension since the width of a highway is normally insignificant compared to its length. The network is formed by connecting each vehicle to the nearest one ahead of it. Information is then routed from up-road to down-road using flooding. In order to manage the amount of information traveling through the network, each vehicle has a ZOR and will only forward the information on vehicles from within its ZOR down the road. Furthermore, clustering is implemented by allowing multiple down-road vehicles close to each other to receive from a single up-road transmitter. In this way, our approach combines previous geocast, clustering, and broadcast based protocols with the concept of dimensional reduction to simplify routing and enable greater frequency reuse. Figure 1 demonstrates our network. The red blocks represent vehicles sending information. The parameter of how far the signals can reach is demonstrated by the circles. The green blocks represent vehicles that are in range to receive the transmissions of the red vehicles.

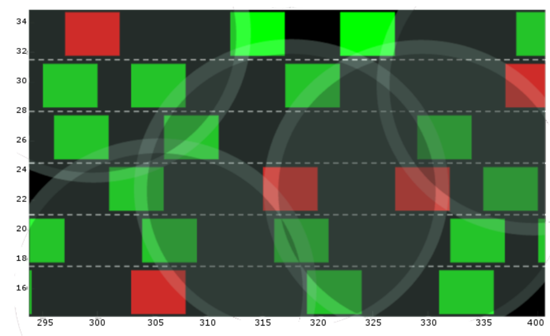

Fig. 1: Simulated Road

B. Band Plan

One of the benefits of the ITS is the ability to achieve greater road throughput by decreasing the space between cars [6]. Our band plan is a proposed modification to the FCC's 7 channel plan for dedicated short range communications (DSRC) [7] in the 5.9 GHz band [5]. We arrived at our scheme by predicting the amount of data the network will need to transmit. Accordingly, we consider a five mile ZOR in front of each vehicle; this will give drivers at least three minutes to react to up-road events when traveling at speeds up to one hundred miles per hour. If there is one vehicle every twenty feet on the highway then up to 1320 vehicles can be included within a vehicle's ZOR. The basic safety information about each vehicle is 312 bits adding up to 411,840 bits per cycle. ITS applications need a 10 Hz update frequency [8] resulting in a data rate requirement of 4,118,400 bits per second (bps). Allowing for forward error correction, future vehicular traffic density increases, expanded ZOR size and channel noise we overprovision the capacity requirement by 40%, resulting in just over 6 Mbps. Following the Nyquist formula with quadrature phase shift keying modulation, each channel should be 1.5 MHz wide. Since the required channel width is so narrow, our system can be integrated with the FCC's current plan by occupying one of its 10 MHz wide channels [9] with six 1.5 MHz wide safety focused channels, each separated by a 91 Hz guard band.

C. Fuzzy Logic

Fuzzy logic allows machines to make decisions using values that are less than precisely defined. Compared to Boolean logic, which only considers two extreme truth values, fuzzy logic works with a varied degree of truth. It uses a vagueness phenomenon by creating a range of logic values from false to true. [10]. For predicting the distance between vehicles in our ad-hoc network, we rate link distances from the most to the least probable. These distances are kept in a database along with the messages the vehicle has received while traveling on the current road.

The two key factors taken into account when considering the link distance will be the curvature of the earth and the two-dimensional position. Since the link distances used in this system are insignificant compared to the curvature of the earth, we use Universal Transverse Mercator (UTM) coordinates to approximate a flat plane for each link. In this plane, the length of the road is the x-axis and width the y-axis. Since the UTM grid simplifies maps by using parallel lines instead of curves, this approximation allows us to calculate link distances simply with standard Euclidean Geometry.

When the connection is made and the distance between two nodes is determined, the link distance is logged into each vehicle's database. In certain scenarios, such as a group of vehicles traveling at a constant relative velocity, the distribution of link distances converges on the Gaussian. This data is used to estimate the most and least probable link distance a vehicle should expect when requesting a new link from the up-road direction. If the request is not answered, the vehicle will repeat the request assuming ever increasing distances until a link is made or maximum transmit power is reached. We consider two methods for updating the predicted link distance. If the link distances in the database form a Gaussian distribution, each iteration will use the link distance described by an additional standard deviation from the mean. I.E the third attempt would be made assuming the mean plus two standard deviations. However, if the distribution of link distances does not form a Gaussian profile, we rely on fuzzy logic to predict the link distance. Our method is to divide the distance it would take to change the projection from membership in most probable distance to membership in least probable distance into five equal steps. After the first attempt, we assume the distance is the initial guess plus an additional step for each subsequent iteration.

D. Link formation

If a vehicle does not have a connection to an up-road source, then it must form a new one in order to gain information about the environment beyond the range of its on-board sensors. There are two main scenarios that result in a node loosing its up-road connection: timeout by the link maintenance algorithm and network topology changes. The first step to forming a new link is to determine which of the six available channels to use by scanning the channel to identify the one with the least power spectral density. Once the channel is determined the vehicle must transmit a request for link signal up-road.

When a vehicle is about to request a link, the question of how much power to use to broadcast this message arises. At this point the node uses the algorithm described in III-C to predict the link distance. Given the link distance, the node calculates the amount of power required to reach a vehicle at the probable location using the two-ray ground reflection model as implemented by Boban et. al. in [11] and sends a request for link signal using that amount of power. The link request process is repeated with increasing values for predicted distance until a link is formed or maximum transmit power is reached. This two-ray model is shown in Figure 2 where: H_1 and H_2 represent the heights of the vehicles, L shows LOS distance between Vehicle 1 and Vehicle 2, X_1 and X_2 illustrate the ground-reflected path distance between vehicles, θ_1 and θ_2 depict the reflection angles, and D represents the distance between vehicles 1 and 2 on the x-axis.

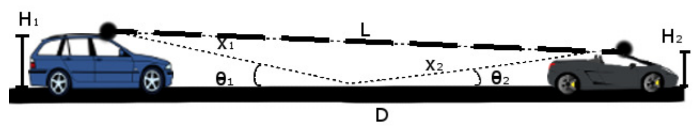

Fig. 2: Two-Ray Ground Reflection Model

For this process to work, vehicles must continuously listen for requests for link signals coming from down-road unless they are already connected to a down-road vehicle. When a request for link signal is detected, the up-road vehicle replies on the same channel as the request with its database of information on all vehicles in its ZOR using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol [12] to minimize collisions. This approach results in minimal distance links since the closest vehicle should receive the request first and have the best chance to claim the channel. This process is represented visually in Figure 3.

E. Link Maintenance

Links must be managed once they have formed in order to prevent undue interference and power expenditure. This management essentially falls into two categories: determining the link lifetime and choosing the appropriate amount of power to transmit down-road. Within the request for link signal, the requester includes a Basic Safety Message (BSM). The receiving node uses the position, velocity, and acceleration data from the message and its own sensors to determine the length of time they will be close to each other without the down-road vehicle passing the up-road vehicle. Since this data is based off an instant in time, we cap the link lifetime at ten seconds. This prevents major topology changes from occurring while transmitters continue to send data down-road to vehicles that are no longer present. After this link lifetime has been

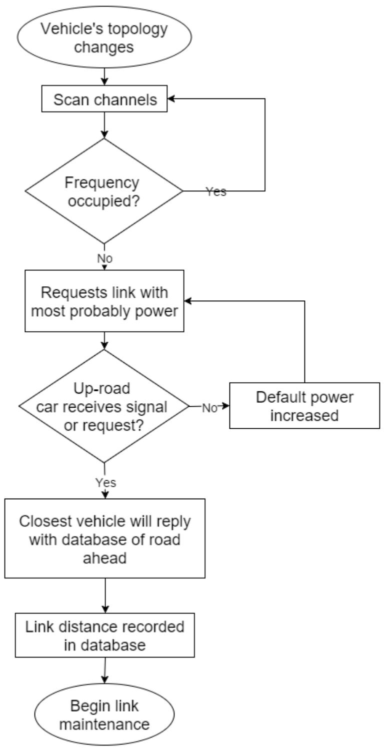

Fig. 3: Link Formation Process

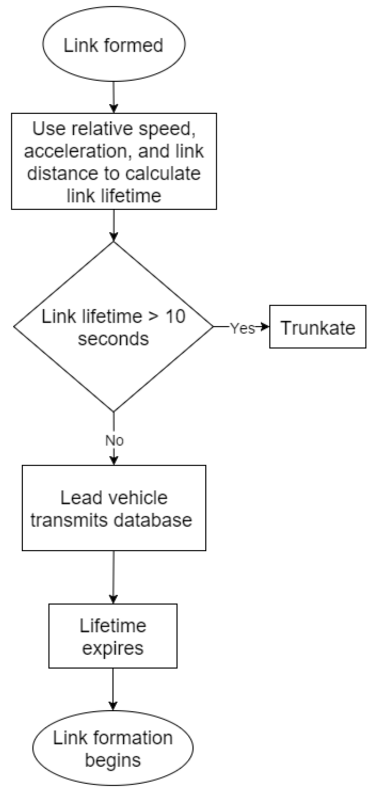

Fig. 4: Link Maintenance Process

calculated, we send the down-road vehicle all the information the up-road car has about vehicles in its ZOR ten times a second until the link lifetime expires.

The other essential part of link formation is power management. The distance between vehicles as a function of time is determined in the process of calculating the link lifetime. During the link formation process, as part of the CSMA/CA algorithm, each transmitter senses the spectrum before acting, establishing an interference threshold [12]. Assuming that the interference at the spatially close receiver is of the same order of magnitude as the interference power at the transmitter, we again use the two-ray method to calculate the transmit power required to achieve the desired signal-to-noise ratio. This power's instantaneous value is used by the transmitter throughout the link lifetime to send its data. Figure 4 shows this link maintenance protocol graphically.

F. Message Format

The whole focus of this VANET is to distribute information about road conditions before users encounter them. We accomplish this by transmitting the raw data about each vehicle without aggregation and allow each node to process it using their own techniques in order to spur advances in VANET applications. The standard for this type of BSM can be found in SAE J2735 [13]. The SAE J2735 BSM thoroughly describes the state of a vehicle using a minimum of fourteen parameters. Although network control only depends on latitude, longitude, speed, and acceleration, we preserve the remaining ten fields for application use. The total size of this BSM is 312 bits and has been accounted for in III-B.

IV. Results

In order to prove the viability of our design, we simulated an ad hoc network of vehicles communicating while traveling down a straight highway as pictured in Figure 1. Our simulation consists of two parts: simulating the road and simulating communications between the vehicular nodes. In the first part, we consider a 1000 meter long section of straight highway, pick one to ten lanes, and populate that stretch of the highway with zero to eighty cars in random positions. We then prepare the road for communications simulation by providing each car with a database of information similar to the segment of road we have already generated randomly. These databases represent the data that each car would have received, had the network been running before the simulation's start. Finally we calculate the link distances from that data for each car.

The second half of the program uses the previously generated configuration to simulate communications through the network. In addition to the assumptions noted in our methodology for simulation, we assume that the cars have all been traveling at the same velocity relative to one another for a short time. In a real implementation of our network, CSMA/CA will be used to determine which vehicle answers a request for information signal. This, however, is impractical for simulation. Instead, we mark each vehicle that is transmitting at a given moment by identifying what the closest up-road vehicle is to

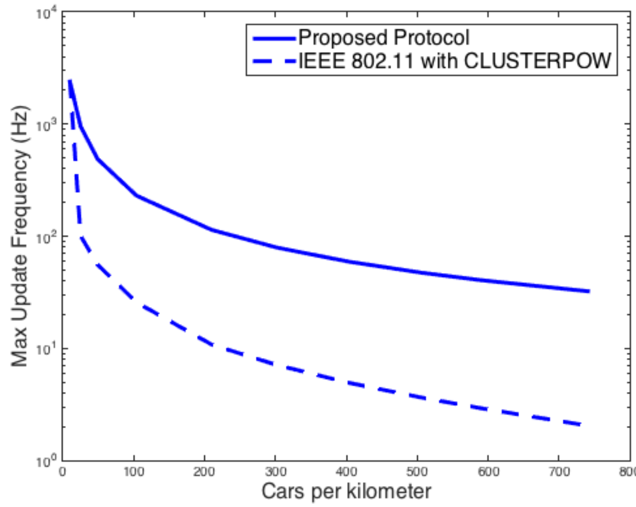

Fig. 5: Maximum Update Frequency per Car Density

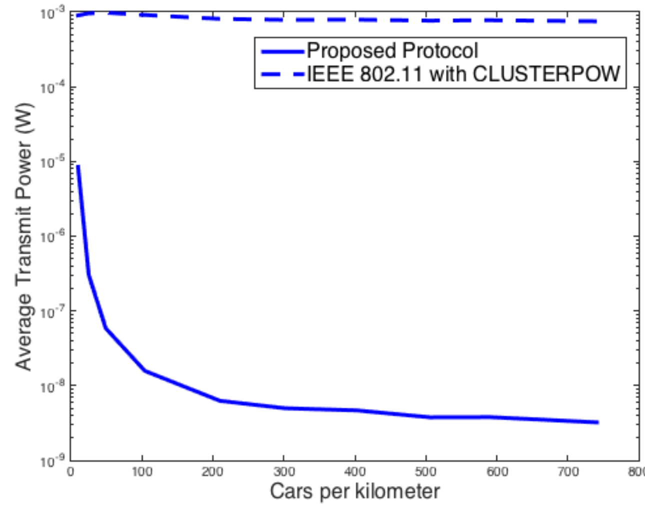

Fig. 6: Average Transmit Power per Car Density

each node. Next, frequencies are assigned for connections; this is determined by finding which channel has the least interference at a transmitter's location as calculated by the two-ray method in [11]. After that we are ready for time step iterations of the network. Each iteration calculates the interference and transmission powers of each node as well as the maximum possible update frequency, using the proposed methodology and a schema based on IEEE 802.11 [14] medium access control protocol modified to use CLUSTERPOW from [15].

Figure 5, Figure 6, and Table 1 show the results of simulating roads with an increasing number of cars. Our method consistently uses two to five orders of magnitude less power throughout the simulation than an IEEE 802.11 VANET modified with a CLUSTERPOW protocol [15]. Since the nodes in the proposed topology are spatially close, we assume all vehicles are in CLUSTERPOW's smallest transmit power category, 1mW. While the demonstrated power reduction is useful for improving the efficiency of electric vehicles, designers of VANETs generally assume unlimited power and computational resources are available [16]. Accordingly, the true benefit of this approach to VANETs can be seen when the density of cars on the road increases. Without intelligent power management, update frequency must be sacrificed to support a large number of spatially close users. This increases the possibility that an important safety event will not propagate throughout the network quickly enough to be of use for incoming traffic. The effect is demonstrated in our simulation of an IEEE 802.11 network with CLUSTERPOW. In this setup, even with a 6 Mbps 100% goodput link, the network's update frequency drops below 10 Hz when vehicle density exceeds one vehicle per every 4 meters of a one dimensional road. This corresponds to bumper to bumper traffic on a two lane road.

		Proposed Network:		IEEE 802.11:	
Number of Lanes	Number of Simulated Cars	Average Transmit Power (Watts)	Average Max Update Frequency (Hz)	Average Transmit Power (Watts)	Average Max Update Frequency (Hz)
1	10	8.448798e-06	2390.19	9.000000e-04	2390.19
2	25	3.042131e-07	956.074	9.600000e-04	100.639
3	49	5.848702e-08	487.793	9.795918e-04	55.672
4	104	1.577975e-08	229.826	9.134615e-04	25.6525
5	210	6.261866e-09	113.818	8.095238e-04	10.7867
6	302	4.980621e-09	79.1452	7.847682e-04	7.09014
7	403	4.661964e-09	59.3098	7.890819e-04	4.92893
8	506	3.766406e-09	47.2369	7.667984e-04	3.63248
9	590	3.791124e-09	40.5116	7.762712e-04	2.9174
10	741	3.225761e-09	32.2562	7.516869e-04	2.03864

Table 1: Results

V. Conclusion

Our VANET is a viable approach for safety applications that is particularly effective in dense networks. We use the geometry of the road to simplify the network to a single dimension, allowing it to form by connecting each vehicle to the closest up-road vehicle. Information travels down the road and spreads across lanes through clustering. This design works by carefully managing transmission power to allow more vehicles to obtain information from the network without compromising the update frequency. To minimize power use during link formation we use fuzzy logic and Gaussian statistics to predict vehicle locations. Given the vehicle location and the noise power in the area we calculate the minimum power that can be used to form a link while maintaining quality of service. The duration of a link is determined from the relative dynamics of the linked vehicles. Our simulation of a straight section of highway demonstrates the viability of this method showing that the network keeps its designed update frequency even when faced with two lanes of bumper to bumper traffic. These features make our network a suitable improvement to current predominate VANET techniques that have difficulty accommodating closely packed users.

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