Active Radar - A Cooperative Approach using Multicarrier Communication

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Abstract—**Vehicular safety systems for collisions or sensing rapid changes in traffic typically use two methods to communicate and disseminate traffic hazards. Many current systems use RADAR systems that transmit a radio wave and sense the reflective waves for angle-of-arrival or time-of-arrival information. Several proposed systems use *vehicular networks* to disseminate information about braking, emergencies or road conditions; when coupled with accelerometer or GPS information, these radio systems may also offer information on speed, traffic density or distance. In-vehicle RADAR systems are relatively expensive; vehicular radio based systems are less expensive.**

In this paper, we present a cooperative technology that combines these two techniques, seeking to adopt characteristics of both systems by employing a *software defined radio* for "cooperative RADAR" and vehicular networking. Our method uses multicarrier wireless communication to *detect* and *disseminate*. Using precise timing and synchronization, we can detect the distance of each of the vehicles, their current velocity and current acceleration or deceleration conditions. Using simultaneous, multi-party acknowledgments, we can rapidly disseminate or determine information about a number of vehicles in an efficient manner.

I. INTRODUCTION

Vehicle safety can be greatly increased by situational awareness - the use of brake lights and turn signals is an obvious demonstration of this. More recently, vehicle safety systems have begun to employ sensing systems such as radar, which have the benefit of immediate utility to the driver, since they do not rely on other vehicles being upgraded. An alternative approach is to use a vehicular radio network to disseminate information about cars using on-board sensors. For example, a vehicle may broadcast a packet indicating that the brakes have been applied, along with information about acceleration and velocity. Although vehicular network systems typically cost less than a similar radar system, vehicular networking is only effective if it is available in many vehicles. However, since vehicular networks can communicate more information than simple velocity and distance and they can do so in non line-of-sight conditions, there are many advantages to such networks. However, one challenge that faces a vehicular network is the *ad hoc* nature of the communication and the increased communication signaling that occurs. Vehicular networks typically use a CSMA/CA protocol for media access; in the presence of dense network conditions, considerable time is devoted to media access overheads.

In this paper, we seek to combine the benefits of radar systems and vehicular networks using a novel paradigm enabled by *software defined radios*. Our system depends on the protocol designer being able to mix PHY-layer and MAC-layer signaling. The basic concept is to rely on *simultaneous reception of limited information from multiple parties*. This is analogous to methods commonly used by people – if we were to query a room to see who ate breakfast, we could do that by asking people to raise their hand to signal that they've eaten. Visually, we can incorporate all the information at once. However, if we posed a more complex query such as "and what did you eat," our senses are unable to discriminate the information and we need a way to share the media. Similarly, radios can receive *orthogonal signals* in a way that the responses to a broadcast by multiple individuals can be decoded – however, we might not be able to identify the individuals or allow complex responses. In our system, we use individual subcarriers of an OFDM signal to represent responses.

Radar systems will only warn the cars in line-of-sight of sudden deceleration. The information will be propagated, though slowly, when each of the cars decelerates. But the time taken by the drivers in vehicles at non-line-of-sight to react to the sudden deceleration may be long enough to lead to disastrous results. Other wireless communication based approaches will generate many communication messages that might overburden the network. By comparison, our protocol might broadcast a periodic "is there a problem" message, and individual cars can "raise their hands" to indicate a problem. Moreover, we can use the timing of the response to indicate the *distance* to a respondent, allowing us to take corrective actions. Because multiple cars can respond simultaneously, the response takes little time, allowing many such broadcast packets to be used. We can also overhear the broadcasts (and responses) of others, allowing us to be informed even when we are not actively querying other vehicles.

II. RELATED WORK

Collision avoidance and on-time alert system for moving vehicles on road has been studied and implemented in different ways, which can be broadly classified in two distinct categories.

The first category studies the motion of the nearest vehicle through radar systems [1]. Radar systems use mm-wave technology to analyze the reflected wave for detecting speed,

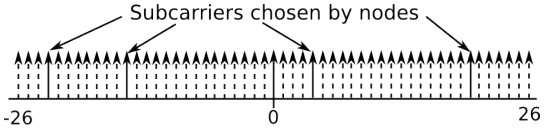

Fig. 1. Schematic illustration of OFDM waveform properties in 20MHz bandwidth

velocity and acceleration of the vehicles in line-of-sight. Radar can be short range or long range, providing both head-on and rear-end collision warnings. Radar based systems do not work in tunnels due to multipath effects and expensive radar units are only available in high end cars. Cheaper models are available using mmwave sensors [2], [3], where the vehicles respond to the query of the transmitter, making the system collaborative. These active radars are supposed to perform better in tunnels, since an active responder only changes the signal and retransmits. However, since the underlying technology still uses radar, it works only in line-of-sight.

The second category uses Dedicated Short Range Communications (DSRC) [4] to generate collision warning. In this technology, location information from a GPS device is combined with the vehicle's velocity and control settings and broadcast periodically. All the vehicles in the neighborhood calculate the chances of collision given they know their own location and speed. However, GPS devices will not work in tunnels, and hence, the whole system shall generate false alarms inside tunnels. In [5], authors used multiple frequencies to transmit different types of messages. However, the overall approach of this technique consumes a lot of bandwidth due to a lot of message passing.

With this background, we present an idea for collision avoidance system, utilizing the benefits of active radar system and wireless communication techniques, which works in non-line-of-sight and tunnels, uses minimum message passing, and should be cheaper as well.

III. PROTOCOL

In this paper, we focus on estimating distance and sudden acceleration or deceleration of vehicles by using *simultaneous transmission and reception* in multicarrier modulation systems. A node periodically transmits a 'Query' message, and adjacent vehicles respond back transmitting a tone in a random subcarrier. If the processing is done at the hardware, the processing time is approximately the same for all the nodes, and the time to respond back only depends on the propagation delay. The original querying node now detects energy in each of the subcarriers to estimate distance and acceleration.

A. Simultaneous Transmission in Multi-carrier Modulation

For this implementation we have chosen the OFDM [6] based physical layer for 802.11a/g as the underlying signaling. Figure 1 shows a schematic illustration of the properties of the OFDM waveform that are needed. A given bandwidth, such as the 2.4GHz band used by 802.11g, is subdivided into 52 *subcarriers* around a center frequency; that center frequency is the "channel" to which an 802.11 radio is set. These subcarriers are orthogonal to each other and do not interfere at the reception. We utilize each of the orthogonal subcarriers to transmit a tone, which is detected at the receiver by measuring the energy in the subcarrier. It is not required to demodulate the signal, since we are not transmitting any modulated information in the subcarrier. The receiver node only detects the time of arrival of the signal to determine the distance. Compared to other models, which require periodic transmission of messages, our method just transmits tones of duration of two OFDM symbols, thus reducing the effective time to transmit response to a broadcast packet.

To summarize, the protocol has the following steps:

1) A node (radio in a vehicle) carrier-senses the channel and transmits a 'Query' packet using the complete bandwidth available to it.
2) All nodes (radio receivers in other vehicles, which are in the first vehicle's radio range) receiving this 'Query' packet immediately responds back by transmitting a tone in one of the subcarriers, chosen randomly.
3) The initiating node detects the time of arrival of signal in each of the subcarriers and calculates approximate distance of any car from it. It receives the composite time domain signal of *all* OFDM subcarriers and performs an FFT to obtain the frequency domain representation of the signal. The start of the signal is determined by performing multiple FFTs during the reception, by moving the FFT window by each sample. A high energy in any subcarrier indicates a tone reception in that subcarrier.
4) Immediately after reception of all the signals, the initiating node again transmits a second 'Query' packet without carrier sensing after SIFS time, so that it again gets access to the channel.
5) This time, responders reply back in the same subcarrier as chosen in the first time.
6) The initiator node compares the time of arrival of the signal this time with the ones at first time and calculates the current condition (constant velocity, acceleration, or deceleration) of the vehicle, which is described in detail in §III-B.

In this protocol, each vehicle chooses a *random* subcarrier to respond back to the 'Query' packet. Since the response uses only one subcarrier, at most 52 vehicles can response simultaneously; however, we are interested in determining if *anyone* responds and when we are concerned with distance, we want to detect the *nearest* respondent.

If two vehicles choose the same subcarrier to transmit their tone, then the initiator node receives the signal first from the nearer node followed and overlapped by the signal from the farther node. In this case, the initiator remains unaware of the current conditions of the farther node; however, we are typically more interested in nearby conditions.

Due to the conversion between the time domain and frequency domain, relatively tight timing synchronization is needed for the signal to be decoded at the initiator node

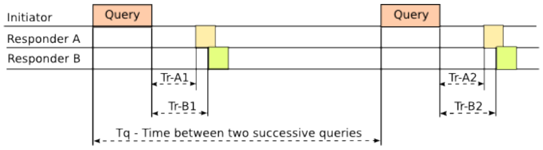

Fig. 2. Timing diagram

to estimate distance; however, that time synchronization is provided by the query message itself.

The following points are to be considered in implementing such a protocol,

- Detecting Start of Signal Arrival in each subcarrier – this is performed by using a sliding FFT window over time with an overlapping factor. This is described in §IV.
- Timing Requirements – the initiator node must have the correct samples to be able to correctly decode the time domain signal to extract the response.
- Orthogonality – the individual subcarriers must not interfere to be able to detect at the receiver.
- Immunity to multipath effect – since a single tone is used to transmit the response, there is very little information that is required to be detected from the subcarriers. Thus even though there will be multipath effect the contribution from those multipaths will be minimal and a Fourier Transform will reveal the strongest frequency components with much lower energy on other subcarriers. So, multipath is really not an issue in this scenario. For the broadcast packet, the receivers are equipped with proper channel estimation and equalization blocks to handle phase offsets along with the cyclic prefix of the OFDM symbols to combat multipath effect.
- Immunity to Doppler Spread – due to very small relative velocity of the vehicles on highway Doppler shift will be minimal and the channel has a high coherence time. Whatever frequency offset results from the mobile environment it should not be significant to force the subcarriers to shift frequency bins and hence can be neglected in this environment as the subcarrier spacing in our implementation ($312.5KHz$) is more that the maximum Doppler shift possible.

B. Estimation of Distance and Acceleration

Figure 2 shows the timing diagram of the signals transmitted on air by the initiator node and two responders, node A and node B. T_r is the time required by the responder to respond to the 'Query' packet. T_r includes processing time at the responder and round-trip propagation delay. If the processing is done at the hardware, the processing time is the same for all the responders, and the time to respond back only depends on the round trip propagation delay. T_rA and T_rB denote the times required to respond by node A and node B respectively. T_rA_1 and T_rA_2 are the response times of A for the first and second queries respectively. These response times are detected by the initiator node and round trip propagation delay is extracted by subtracting the processing time from T_r. Electromagnetic waves propagate at the speed of light, which is approximately $3.0 \times 10^8 m/sec$. So, if a node is $100m$ away from the initiator node, waves propagate $200m$ round trip, which takes approximately $0.06\mu s$. This estimates the distance of the vehicle from initiator vehicle. The distance, we calculate both the times and effective acceleration or deceleration condition of the vehicle. If T_rA_1 equals T_rA_2, then relative velocity of the vehicle with respect to the initiator vehicle is constant and no warning is generated. If T_rA_1 is less than T_rA_2, then the relative velocity of the vehicles are changing. But in this case, either the responder is accelerating away, or is decelerating away from the initiator vehicle. Hence, no alert is generated. However, if T_rA_1 is greater than T_rA_2, then vehicle A is either in front of the initiator vehicle and is pushing brakes, or is behind the initiator vehicle, pumping the accelerator. In this scenario, we generate a collision warning devoid of direction.

This procedure may lead to circumstances when a minor change in the velocity would result in alarms. Hence, more accurate measurements can be done based on the T_q, which is the time between two successive queries. Let D_{A1} and D_{A2} are the estimated distances between vehicle A and the initiator vehicle recorded after an interval of T_q, and $D_{A2} < D_{A1}$. Then, the relative velocity of node A with respect to the initiator vehicle is $(D_{A1} - D_{A2})/T_q$. If this value is within some tolerable limits, then no alarm is generated. This threshold has to be set based on experiments and is not included in the current focus of the paper. Also, the alarm can have different status based on the distance and relative velocity of the vehicles.

IV. HARDWARE IMPLEMENTATION

To demonstrate tone transmission and simultaneous reception of OFDM, we implemented a prototype using a software defined radio platform. The basic design [7], [8] involves an OFDM transceiver on a Virtex-IV FPGA along with a custom front-end radio operating in 2.4GHz ISM band. The tone transmission is done by selecting one of the subcarriers in the transmitter design [7]. The initiator node receives a composite additive signal from all the neighbors and, depending upon the number of users, the number of distinct frequency components in the signal will vary, as shown in Figure 3.

A simple Fourier transform at the initiator will reveal the tones in the signal. Observing the magnitude of the Fourier transform we can identify high energy subcarriers. Our hardware can use up to a $256pt$ FFT and thus can detect up to 255 vehicles as no energy is transmitted at the d.c. subcarrier. However to estimate the distance and time difference of responses from different vehicles we need to perform the FFT continuously as a sliding window over the received samples with an overlapping factor of as much as 254 samples. Since the sampling time is $12.5ns$ it gives a time granularity of $12.5ns$ which is equivalent to $3.75m$ of distance between two cars. However, the transmission time for different responders depend on their distance from the initiator node. Therefore it is important for the initiator node

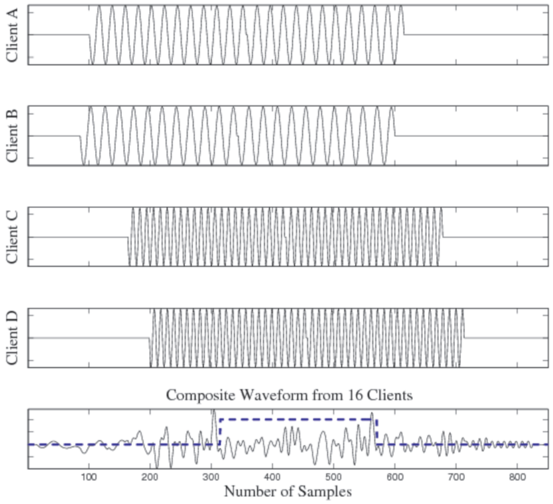

Fig. 3. Timing offsets between responses and FFT window

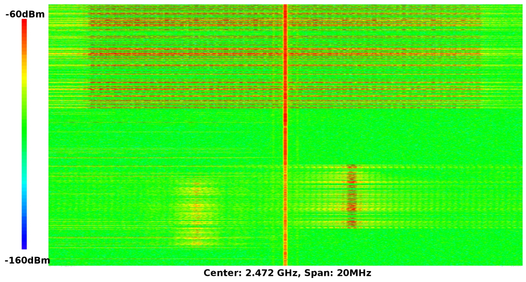

Fig. 4. Waterfall plot using two prototype radio platforms, X-axis showing frequency and Y-axis showing time

to wait for a specific time T, dependent on propagation delay, to insure all responders have decoded the 'Query' message and the response tone have propagated to the originator. But in context of vehicular networks we argue that this time T will be negligible due to relatively close proximity of the vehicles.

A. *Results From Hardware*

One of the radios was used to transmit one broadcast packet using the standard 802.11a/g PHY specification. The receivers decoded the broadcast packet and prepare the response on a random subcarrier and transmits a tone. The receivers were placed at two widely-varying distances from the transmitter to highlight the impact of near-far differences in responders. We used a vector-signal analyzer to capture the physical data. Figure 4 shows that the node transmitting in subcarrier $+8$ has a higher signal power (closer to the initiator node) compared to the one transmitting using subcarrier -8 (farther from initiator node). Also different time of arrival of the responses show the near-far effect. The waterfall plot also shows the broadcast packet at the top of the graph – that packet is transmitted first using the full spectrum available.

B. *Efficiency and Generality*

To understand how much more efficient it is to use physical signaling as we've done, consider the costs of transmitting a message using the 802.11g PHY that's the basis for our extension. A normal message requires a 20μs preamble to be transmitted and then, at best, each 48×6 bits takes one OFDM symbol time (4μs) to transmit. Thus, a moderately sized 64 byte message, would take at least $20 + 4 \times 3$ or 32μseconds. After a 2μsecond "SIFS" period, vehicles would normally respond using a similar message format. Thus, an response to a standard 802.11g packet would take another $\approx 32\mu$s. By comparison, using this PHY layer signaling protocol *all* vehicles can provide acknowledgment information within two OFDM symbol periods, or a total of 8μs. Moreover, we can use the time of arrival information to estimate distance; this estimation favors responses for near-by vehicles, which is consistent with most traffic management queries ("is there a problem").

V. CONCLUSION

The idea of using multicarrier communication in vehicular safety applications is innovative, and incorporates the benefits of existing applications, while excluding the shortcomings of the current solutions. Instead of simulating our idea, we have gone a step ahead and actually implemented a prototype in hardware, and shown results in static scenario. In future, we plan to extend our work and show results from moving vehicles.

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