Planning of Low-Cost 77-GHz Radar Transceivers for Automotive Applications

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INTRODUCTION

The use of electronics in the automotive industry will reach (or has reached in some experimental prototypes) an inflection point at which the *control* of vehicles will evolve (or has evolved) from *"manual"* to *"autonomous"* navigation. In a not too distant future, radars will be used in lane change assistance, blind spot detection, adaptive cruise control, collision warning, and pedestrian detection. But a more critical role will be automatic guidance of the car on the road. It is projected that by the year 2020, traffic congestion in many cities around the world will reach unresolvable levels unless vehicles incorporate autonomous control so as to coordinate their movements for optimum traffic flow.

Control of vehicles in a surrounding environment such as a parking spot or a busy road will rely on the use of as many as six radars in each vehicle. The radars determine the distance between the vehicle and the surrounding objects as well as the speeds of other vehicles, continuously adjusting the position and speed as with other components used in the automotive industry, radars will find widespread usage only if their cost can be absorbed easily by Moghavvemi and Tan [1]. Thus, each radar system must cost no more than a few tens of dollars (www.triquint.com, www.hittite.com).

The key to prevent driving accidents by automotive radar systems at high speed is to have optimum and accurate estimation of position representation and fast visualization of the environment.

For example Klein [2] market research reports the following: *"the Intelligent Transportation System (ITS) in the United States in 2008 has reported the following data: (1) 2.6 million traffic crashes (42,000 fatalities, 2.6 million injuries, $250 billion in costs); (2) $80 billion cost of urban traffic congestion (4.2 billion hours of delay, 2.9 billion gallons of wasted fuel)."*

Further market research data on these systems can be found in Dr. Progri's chapter 5 of his new book on *Indoor Geolocation Systems—Theory and Applications* [3].

The is organized as follows: The *Intelligent Transportation System* section discusses the previous radar systems in traffic monitoring and controlling applications. The *System Design* section describes a detailed system diagram level design such as low-cost antenna design for 77-GHz operation and the design of the CMOS transceiver and the local oscillator (LO) and finally, Conslusions are presented in the *Conclusion* section.

INTELLIGENT TRANSPORTATION SYSTEM

Humans as a species are not designed (or created) to fly or run (i.e., *"drive"*) at high speeds by themselves. Take birds, for instance, that fly by the hundreds in a pack or fish that swim in a large pack (fish school) or zebras that run by the large numbers. They rarely crash into each other. It is a new research study on what kind of bio-system they are equipped with to fly/run or swim at very high speeds at a large number and in an environment that they did not design. For humans, most road accidents are due to driver error in judgment or poorly-designed transportation systems because it did not or does not take into account the fact that we (humans) were not designed (by God or evolution or a combination) to do these things at high speed) which leads to driver delay reaction to other speeding vehicles or obstacles in the road. In particular, following too closely and delay in anticipating the adjacent vehicle momentum are the most common prevalent errors. The automotive radar system is able to report the range and

relative velocity of behind, beside, and in front of vehicles or any other obstacles with high precision and accuracy in order to reduce accidents caused by driver errors by Moghavvemi and Tan [1]. Some methods have been used over the years such as sonar, infra-red or microwave radiation. Sonar methodology has the disadvantage of dependency of speed of sound in air-to-wind speed and temperature, whilst microwave radiation has the ability to penetrate power over visible light when used in the presence of rain or fog by Moghavvemi [4].

Intelligent Transportation System

ITSs have been widely used in the US, Japan, and Australia to achieve intelligent traffic control by analysing information such as vehicle position, momentum, speed, and type. Numerous methodologies have been integrated in ITSs to extract this information from data signal processing algorithms by Barrientos et al. [5]. In previous methods, vehicle information was extracted by a vehicle detector (VD) device which was planted mostly on the surface of the road. Different types of VD devices are still in use such as infrared VD by Kagesawa et al. [6]; image-processing VD (IPVD), looped VD by Sun et al. [7] and frequency modulated continuous wave (FMCW) VD. When a vehicle is passing through the VD sensing range, VD detects the vehicle positioning with respect to time to evaluate type and speed of the vehicle. IPVD uses image processing techniques such as texture or feature classification, to estimate the vehicle type and speed by Zehang et al. [8]. In infrared VD devices by Nelson [9], fuzzy interference systems for vehicle classification is used in infrared images; however this type of VD maintenance is troublesome. All of the above-mentioned VDs function poorly at night time or in bad weather. FMCW-VD transmits microwave continuous frequency. Kanhere and Birchfield [10] suggest that the transmitted and reflected frequencies are compared and consequently the vehicle information such as type and speed can be analysed. Wang and Lien [11] propose that a channel-awareness VD is implemented to acquire traffic information. Tx and Rx antennas were operating at 2.44 GHz with 800 MHz bandwidth. The method can easily detect multiple vehicles simultaneously and has simple installation compared to other references. In Khammari et al. [12], an automotive radar sensor demonstrator at 77-GHz with SiGe chipset is reported. Mechanical scanning, parallel fixed beams with uni-pulse direction of arrival (DOA) switching phase array with digital beam forming (DBF) are the most commonly used automotive radar sensors Sappa et al. [13]. A SiGe chipset is able to fully integrate receiver architectures with complete RF-path per channel, which make it superior in target detection with respect to switching phase array technique. In switching phase array, moving target is as no phase-aliasing. 77-GHz FMCW radar with DBF and super resolution DOA applications is reported in Wei et al. [14]. The vehicle radars receive echoes from target surroundings such as roads and buildings. These echoes are called clutter, which may be higher than vehicle echo. In Giancarlo et al. [15] clutter

suppression scheme methodology is reported which improves the target detection accuracy by summing all of the radar echoes available by the target vehicle(s). In heavy road clutter, detection of multiple targets is possible by utilizing pulse integration and occurrence probability.

Automotive Radar Navigation Method

One of the many challenges in automotive navigation is the difficulty of defining the environment of the vehicle which applies to every situation such as different weather or different texture classifications in surroundings. *The key to prevent driving accidents by automotive radar systems at high speed is to have optimum and accurate estimation of position representation and fast visualization of the environment.* One approach to this optimization is introduced by Jianxin et al. [16] and its references which are based on gridding map on very small scale such as 60 m × 60 m grid cell. By focusing on each cell, the algorithm helps the vehicle to react based on its momentum and other vehicles or obstacles position and direction of movements. This method will face problems in uphill and downhill slope surfaces. The algorithm is programmed to use mean height to evaluate terrain, which does not result in accurate evaluation in determining the position and momentum of adjacent vehicles.

SYSTEM DESIGN

Preparing the detailed descriptive and virtual interpretation of perspective systems based on practical requirements for Geo-location of RF Signals (GRFS) systems offer an overview of the best practice and innovative techniques in the art of GRFS systems which consists of local coordinate point-of-view into: 1-indoor, 2-urban, 3-suburban, 4-global, and 5-satellite by Progri [17]. Herein, we discuss the urban GRFS systems description requirements for automotive coordinate point-of-view by Progri [18].

The effective range of urban GRFS systems operation is from 100 m up to 10 km on the ground, in the air, in space, in or on water [18]. We discuss the urban-ground GRFS system requirements for radar applications in the next section.

Urban-ground GRFS systems in Progri [18] are used in most or all metropolitan areas, big and small cities, commercial, residential, government facilities, factories, hotels, industrial franchises, etc. monitoring purposes. The proposed radar system is a pulse Doppler radar type which employs high Pulse Repetition Frequency (PRF) radar. It uses the Doppler frequency shift to extract moving targets in clutter and it also has no blind speeds in Doppler, but it does have range ambiguities. Range-ambiguity resolution in high PRF is performed by modulating the transmitted signal and observing the phase shift of the modulation on the return echo even at low amplitude level. As such, the systems must achieve a wide dynamic range of transmitting distance. For automotive applications, a transmitted power of +10 dBm (10 mW) and a receiver with a sensitivity of −90 dBm allow a total path loss of 100 dB, which translates to a range of 15 m at 77-GHz for an antenna gain of 0 dB. However, it is

proposed that each side of the vehicle will use separate radar with directional antenna having gains as high as 20 and 30 dB for sides and back-front radars to increase the range up to about 100 and 150 mm, respectively.

The proposed radar system for vehicular application initially is point-to-point, but with coding multiple transmitting RF signals from 75.8-GHz up to 76.5-GHz with 10-MHz bandwidth and decoding at the receiver, the radar system can be point-to-multipoint, as well. The RF signals for urban GRFS systems are mainly for mobile systems and Metropolitan Area Network (MAN) systems which are discussed in great detail in chapter 3 of Dr. Progri's book *Geolocation of RF Signals – Principles and Simulations* [18]; these standards have three main parameters: 1-data rate (b/s), 2-frequency (Hz), and 3-range (m), which does not interfere with the proposed system operating frequency. The urban-ground GRFS system block diagram is illustrated in Figure 1.
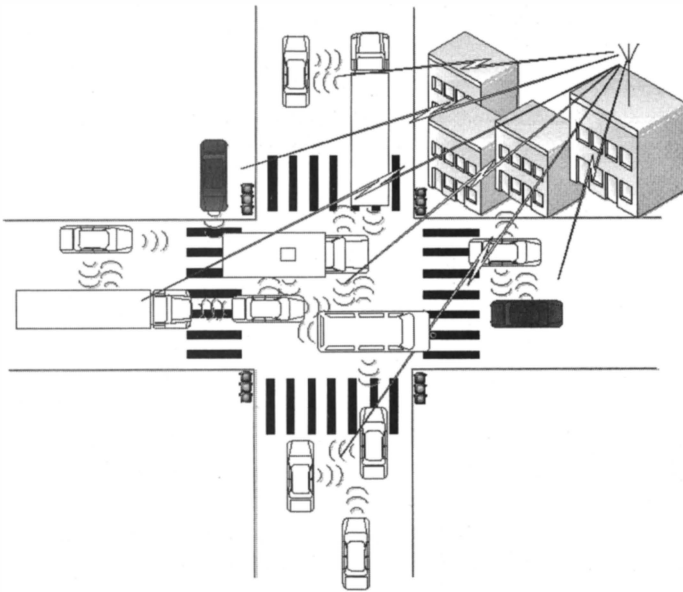

(a)

Fig. 2A. Proposed Radar Architecture

(b)

Fig. 2B. Proposed Transceiver Chip Architecture

(c)
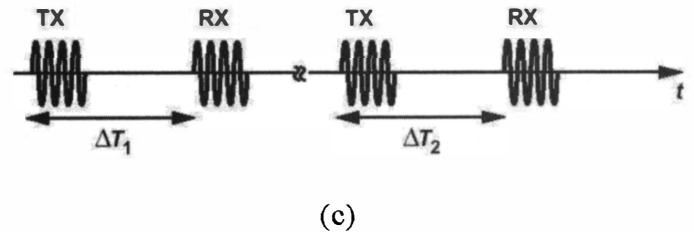
Fig. 2C. Sweep of LO Delay to Determine Accurate Round-Trip Delay

Fig. 1. Urban-Ground GRFS Systen Block Diagram

Figure 1 describes the urban-ground GRFS for urban outdoor geo-location systems. In general, urban-ground GRFS systems are able to locate both positioning transmitters and RF sources. There are several advantages to urban-ground GRFS system such as no backhauling required, flexibility in locating nodes, and provide decreased transmit power and interference. The urban-ground radar system is designed to identify any objects in its surrounding area up to 100 m with centimeter range resolution which is perfect for automotive traffic. A sinusoidal pulse is applied to the antenna by the PA and transmitted toward the target. The reflected signal arrives at the receiver after some round-trip delay ΔT_{RT}; see Figure 2A. The transceiver chip includes a receive path, a transmit path, and a local oscillator. The full integration of the transceiver leads to a compact system with
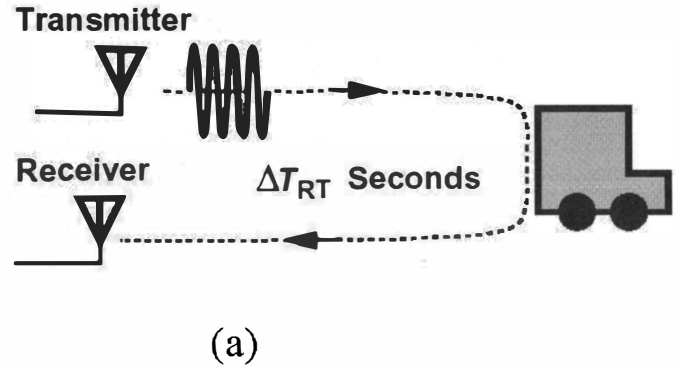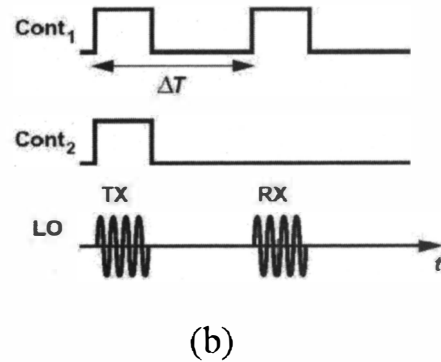
a small number of components offering a cost-effective advantage. However, if designed in CMOS technology to reduce the cost, the transceiver chip cannot readily produce high output power. Therefore, an external PA, the HMC-AUH318 from Hittite, boosts the power delivered to the antenna to about +10 dBm.

Next follows a brief description of (3D) Principle of Operations' Distance Estimation.

(3D) Principle of Operations' Distance Estimation [1]
Accurate bios estimation error is crucial to the automotive radar system. Robust and efficient numerical implementations of bios estimation error is presented below.

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[1] The reader may find the analytcal derivation details of the (3D) Principle of Operations' Distance Estimation can be found in chapter 4 of Dr. Progri's book on *Geolocation of RF Signals – Principles and Simulations* [18].

Herein we discuss the bias estimation model for 3D radar considering platform attitude error. The 3D principle of operations' distance estimation is shown in Figure 3.

Assume we have two antenna array located in P_1 (X_1, Y_1, Z_1) and P_2 (X_2, Y_2, Z_2) and one RF source is located at P_3 (X_3, Y_3, Z_3) and P_3 is not on the same line as P_1 and P_2. If the center of the 3D coordinate system is equally placed between the two antenna arrays, and the distance between them is noted as d therefore the antenna location can be rewritten as $P_1(-x, 0.0$ and $P_2(x, 0,0)$. Because we know the direction of transmitting signal from RF source then (α_1, α_2) and the angles (β_1, β_2) which could be both azimuth and elevation angles depending on the application and configuration of the system are known.

(a)

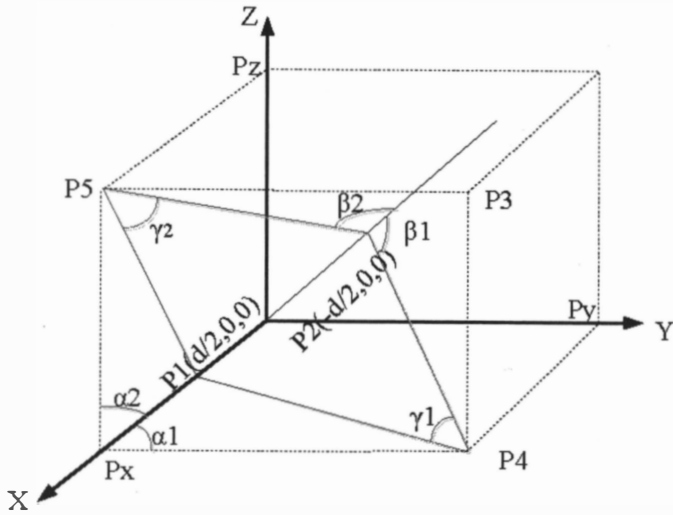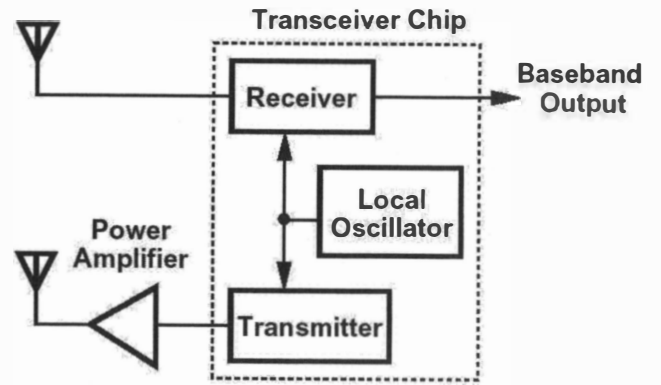**Fig. 4A. Proposed Radar Architecture**

Fig. 3. One RF Source at Point P3 and 2 Antenna Arrays at Points A and B in 3D-Dimension


(b)

Proposed Radar Architecture

The system and architecture design proposed herein can be utilized at any frequency. While conventional automotive radars operate at 26 GHz, the trend is to move to 77 GHz so as to achieve a higher resolution.

Very wide application ranges from wireless local area network [18], IEEE 802.11, IEEE 802.15, WiMAX Fan et al. [19], Digital TV (DTV), Satellite TV, 4G WCDMA Mobile Network, Wi-Fi, Low-enforcement networks and radars to emergency networks such as mobile responder communication networks public safety Balachandran et al. [20], the wireless broadband (WiBro) system for broadband wireless internet services Seung-Que et al. [21] and WLAN technologies in medical facilities to support medical care delivery with high efficiency are currently employed in urban-ground GRFS systems. Other instances are the low-cost integration of WiMAX with Wi-Fi and bandwidth sharing using IEEE 802.16e/IEEE 802.11e standards Progri [22], WiMAX
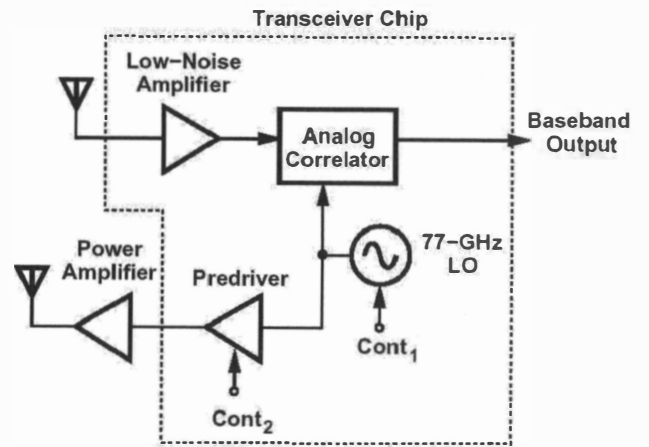
Fig. 4B. Proposed Transceiver Chip Architecture

femtocells Kim et al. [23] and an evolved cellular system architecture incorporating relay stations. There are several standard solutions for wireless point-to-point or point-to-multipoint or multipoint-to-point or multipoint-to-multipoint which include residential, commercial, hospital, vehicular, and etc. applications Bo et al. [24].

The system proposed herein achieves this level of performance while maintaining a low cost through integration. Figure 4A shows the overall system. It consists of two directional antennas, a single-chip transceiver, and a power amplifier (PA). Figure 4B depicts the proposed transceiver chip architecture. The transmitter incorporates a 77-GHz LO whose output is applied to a pre-driver stage.

Tale 1. Overview of Geometrical and Radiation Characteristics of Different Antenna Configurations

Dimensions of Patch Bandwidth and Gain of Antenna	Patch Antenna Configuration		
	Suspended Patch	Partially Suspended Patch	Conventional Patch
Patch Dimension (mm)	1.65×1.7	1.46×1.7	0.84×1.2
Height of Patch above ground (mm)	0.2	0.327	0.127
−3 dB Bandwidth (GHz)	7.5	15.4	3.1
−10 dB Bandwidth (GHz)	9.7	20	4
Maximum Gain (dB)	9	9.3	6.4

This stage drives the external PA as well. Both the LO and the pre-driver can be turned on and off at high speeds. In the transmit mode, the LO and the pre-driver are turned on for about 1 ns, producing a pulsed sinusoidal signal.

Transceiver Design

The integration of the transceiver in CMOS technology proves essential to lowering the cost and form factor of the radar system. However, the limited speed and supply voltage of CMOS devices present many challenges to the design. The transceiver proposed herein is designed so as to relax the performance required of each building block, allowing robust realization in standard CMOS technology.

The most promising modulation scheme for high-resolution radars is based on pulsed continuous-wave (CW) signals. The transmitter generates a sinusoidal signal for a short period of time. This pulse sinusoidal signal travels, hits the target, travels back, and is sensed by the receiver. The round-trip delay of the pulse represents the distance, and the Doppler shift in the frequency reveals the velocity of the target.

While other modulation schemes such as FMCW have been used in radars, it has been recognized that for high resolutions, especially at short distances, pulsed CW is superior to FMCW.

The receiver consists of a LNA and a correlator. The objective is to delay the LO by ΔT and correlate it with the received pulsed sinusoid signal. If the result of the correlation reaches a maximum, then the on-chip delay applied to the LO is equal to the round-trip delay experienced by the pulse: $\Delta T = \Delta T_{RT}$ shown in Figure 2A.

In addition to the millimeter-wave low-noise circuit design, the receiver poses another difficult challenge: a delay line that can delay the 77-GHz LO by as much as several hundred nanoseconds (i.e., the round-trip delay

from a vehicle 100 m away). If built on-chip, such a delay line exhibits a high loss at these frequencies. To resolve this issue, the proposed architecture simply turns the LO on again after ΔT seconds rather than actually delay it by this amount. This time, the pre-driver is kept off. Thus, the transmitter remains inactive while the receiver performs correlation on the *"delayed"* LO and the received signal shown in Figure 2B.

The Tx and Rx modes are alternately enabled at a relatively high rate (e.g., 100 MHz) and the value of ΔT_1 is varied in small steps until the correlation reaches a maximum shown in Figure 2C.

The correlator can be realized as a mixer followed by a low-pass filter, with the average output representing the strength of the correlation, and hence, the distance to the target. Also, the filtered output of the mixer contains a low-frequency component that arises from the Doppler shift, thereby representing the velocity of the target.

Antenna Design Planning

The automotive radar sensors have become feasible since the 1990s. The demand to enhance the performance level and deduct the end-user cost simultaneously has led to tremendous growth in the automotive vehicle radar systems. Antenna patch plays a great role in these systems.

The frequency precision, frequency bandwidth, and gain are the main concerns in antenna patches; so far lens Zhou et al. [25] and microstrip patch antennas Ndip et al. [26] have been very popular due to their stability of low-cost mass production. Plus array antenna configurations are more suitable for automotive radar systems.

It was reported in Ndip et al. [26] that with the bandwidth of −10 dB, the partially suspended patch has the largest impedance bandwidth of 20%, the suspended patch, 9.7%

and the conventional patch has the least impedance bandwidth of 3%.

The maximum gain observed from each patch indicates that suspended patch has the most and conventional patch has the least gain (see Table 1).

For this automotive radar system, two horn antennas used for receiving and transmitting paths will be designed for a gain of about +25 dB and dimensions of $60 \times 20 \times 80$ mm^3. The elevation and azimuth beam widths will be 4° and 15°, respectively. A WR15 waveguide will connect the antenna to a transition on the assembly, and the transition connects to the input of the receiver or the output of the power amplifier. The antennas will be made of brass with 5 μ gold coating.

CONCLUSION

The key to prevent driving accidents by automotive radar systems at high speed is to have optimum and accurate estimation of position representation and fast visualization of the environment.

The big picture is the integration process of the inputs provided by this system with other objects in the environment. This is a topic of research for an interdisciplinary research with the hopes of developing very sophisticated ITSs for higher safety standards.

A complete 77 GHz automotive radar system is planned and analyzed herein. 3D bias error estimation for a 2 array antenna is modeled as well. The proposed architecture is able to acquire multiple vehicles position, and speed, simultaneously and it is very cost-effective and easy to construct. Also an extended recently used automotive radar system for traffic monitoring application is presented and compared with each other. A 77-GHz horn antenna is modeled and analyzed for better efficiency, larger bandwidth, and radar gain power. The ITS system engineering task is very challenging and the proposed system is a starting point into more elaborate design and discussion.

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