A Homodyne Low Cost Uplink Receiver for Digital Short Range Communication Systems

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***Abstract* — In this paper we propose an architecture for a homodyne receiver for Dedicated Short Range Communications (DSRC) for Road Traffic and Transport Telematics (RTTT). The receiver was thought with the new European standard EN12253 in mind, although its architecture may be adopted in other scenarios.**

Index Terms — CEN, direct conversion, DSRC, homodyne, quadrature, receiver, RTTT, standards, uplink.

I. INTRODUCTION

Dedicated Short Range Communications (DSRC) is a well established technology when it comes to Road Traffic and Transport Telematics (RTTT). Automatic toll collection, automatic parking payment and fuel station payments are some of the current applications of this technology. DSRC is being pushed to other services, like car-to-car communications, intelligent highways, and so on. New European Standards are being developed, namely EN12253, EN12795, EN12834 and EN13372. When it comes to IEEE, there are two subcommittees involved DSRC program: SCC32 DSRC Subcommittee, and the P1556 Subcommittee.

This paper describes a Road Side Unit (RSU) receiver architecture which follows EN12253 [1], although it can be extrapolated to other systems. The European Committee for Standardization (CEN) standards aim simple transactions at a relatively low rate, meant mainly for vehicle identification, access control, toll collection, parking fees and fuel payment. A compatible On Board Unit (OBU) is described on [2].

As the present standard, communication takes place between an RSU and an OBU and vice-versa. Communication from RSU to OBU is named Downlink, while in the reverse sense is called Uplink. This paper describes a possible architecture for the Uplink receiver.

II. SIGNAL GENERATION FOR THE UPLINK.

Communication takes place around 5.8 GHz both for Downlink and Uplink. However, the OBU has no local oscillator hardware inside for microwave frequencies: it reuses the downlink carrier generated at the RSU. It is then needed that the microwave downlink carrier is always turned on.

The baseband signal generated at the OBU has a 250 kbit/s rate and is NRZ coded. It modulates a locally generated 1.5MHz or 2.0MHz sub-carrier with phase shift keying (PSK). Phase transitions must occur when the sub-carrier's amplitude is zero.

Up-conversion is achieved by mixing sub-carrier with the microwave carrier from the RSU. This is depicted in Fig. 1.

Thus, is very tempting to employ a homodyne receiver at the RSU, taking the 5.8GHz source as the local oscillator for down-conversion. Of course, we know that the local oscillator has the same frequency than the carrier of the uplink signal, but the phase relationship is unknown. If the OBU is moving, which is the most common case, there is a slight frequency deviation due to Doppler effect. The proposed receiver deals with these problems seamlessly.

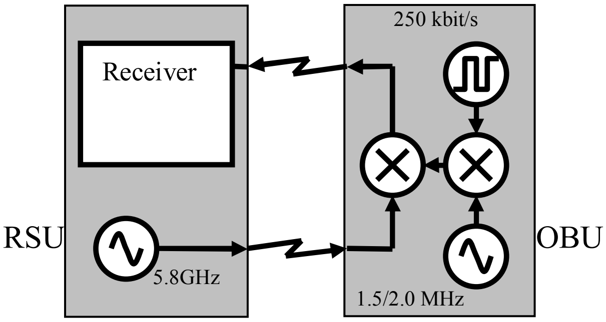

Fig. 1 - Uplink signal generation

Also, it seems homodyne receivers are overlooked. Most of them refer to the Weaver architecture [3][5] and their aim is image-frequency rejection on SSB reception. Clearly, this is not our case. Most of them rely on locking the local oscillator on the incoming signal, such as described in [4]. Again, we do not want to use a second oscillator, so input phase relationship with the oscillator is unknown. This is known as an incoherent receiver [6]. Homodyne receivers also have several advantages, such as those recognized on [6]: reduced number of RF circuits, no mirror frequency problems, no adjustments to be done, ease of integration, easy (baseband) filtering.

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III. BASIC IDEA OF THE RECEIVER

The following quantities are defined:

ω_c: microwave carrier's angular frequency;

ω_{sc}: OBU's generated sub-carrier's angular frequency;

d: distance between RSU and OBU;

It is assumed, for the sake of simplicity, that there are no other signal delays except those introduced by d or those phase shifts explicitly shown on figures. For simplicity of explanation the amplitude factors are dropped in the analyses contained in this paper whenever it is unimportant for the overall understanding.

The carrier generated at the RSU can be expressed as

$$x_c = \cos(\omega_c t) \tag{1}$$

This carrier arrives to the OBU with a certain phase delay introduced by d as follows:

$$x'_c = \cos(\omega_c t - \frac{\omega_c}{c} d) \tag{2}$$

The PSK-modulated sub-carrier can be expressed as

$$x_{sc} = P\cos(\omega_{sc} t) \tag{3}$$

where P is the information signal, which can take the values "+1" or "-1", resulting in a 180 degrees phase shift each time P is changed.

Mixing x_{sc} with x'_c results in

$$x_{obu} = P\cos(\omega_{sc} t)\cos(\omega_c t - \frac{\omega_c}{c} d) \tag{4a}$$

which can be expressed as

$$x_{obu} = \frac{P}{2}\left\{\cos\left((\omega_c - \omega_{sc})t - \frac{\omega_c}{c} d\right) + \right. \\ \left. + \cos\left((\omega_c + \omega_{sc})t - \frac{\omega_c}{c} d\right)\right\} \tag{4b}$$

This signal has to travel back to the RSU. Since $\omega_{sc} << \omega_c$ we can approximate the phase delay of both components to the delay of the carrier. Hence, when this signal arrives to the RSU it can be written as:

$$x'_{obu} = \frac{P}{2}\left\{\cos\left((\omega_c - \omega_{sc})t - 2\frac{\omega_c}{c} d\right) + \right. \\ \left. + \cos\left((\omega_c + \omega_{sc})t - 2\frac{\omega_c}{c} d\right)\right\} \tag{5}$$

If this signal is beaten with the carrier, after low-pass filtering and rearranging the expression we obtain

$$x_{m1} = \frac{P}{2}\cos(2\frac{\omega_c}{c} d)\cos(\omega_{sc} t) \tag{6a}$$

Looking at the above expression, one can break it down in the following factors: P is the information signal (-1 or 1, which results in an effective phase inversion), $cos(\omega_{sc})$ is the subcarrier and $cos(2\omega_s d/c)$ is an amplitude factor dependent on the distance between OBU and RSU. Excluding this last factor, we can easily conclude that the down-converted signal is the PSK-modulated sub-carrier. However, it is also apparent that the signal's amplitude is widely dependent on the distance between OBU and RSU due to the factor $cos(2\omega_s d/c)$. In fact, the amplitude is zero for each point the cosine is zero. For a 5.8GHz carrier, this means a zero each 1.3cm (1/2 inch) approximately.

Although this is a homodyne receiver, we never know the phase difference between the output carrier and input carrier.

To avoid this problem a second mixer is added for down-conversion, with the local oscillator fed with a 90º phase shift. The receiver now looks as shown in Fig. 2. The second signal becomes:

$$x_{m2} = \frac{P}{2}\cos(\omega_{sc} t)\cos(2\frac{\omega_c}{c} d - \frac{\pi}{2}) \tag{6b}$$

The receiver structure is, for now, an I/Q one. Note that x_{m1} and x_{m2} are the very same signal with different amplitudes. When the amplitude is zero in one branch, it is maximum on the other branch.

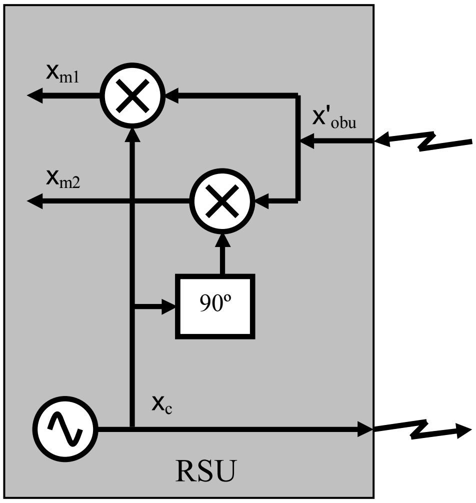

Fig. 2 - Receiver down-converter architecture

This solution assures that we get a non-zero signal at least in one branch. There is no need for a IF oscillator, nor IF stages. Representing x_{m1} and x_{m2} in a phasor diagram, we get a result like those depicted in Fig. 3. The two phasors can be either in-phase or opposite phase, depending on the signs of

$cos(2\omega_s d/c)$ in x_{m1} and $cos(2\omega_s d/c-\pi/2)$ in x_{m2}. Of course, these signs are dependent on the (unknown) distance *d* between OBU and RSU. The relative amplitude of those phasors is also dependent on *d*.

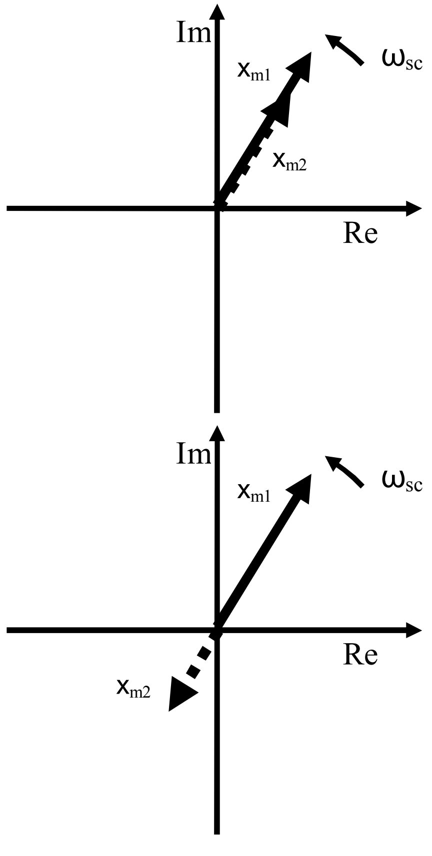

Fig. 3 - Phasor diagrams for xm1 and xm2

However, a second question arises: how can these signals be combined in order to extract the information signal? Since signals x_{m1} and x_{m2} can be either in-phase or opposite-phase, they cannot be just added together.

The solution is to rotate one of those branches 90º, since two orthogonal vectors added together are always non-zero if at least one of them is non-zero. This condition is assured as seen above. The diagrams on Fig. 4 arise from those on Fig. 3 lagging x_{m1} by 90º (resulting in x'_{m1}). Adding x'_{m1} with x_{m2} we get x_{out} (always non-zero).

$$x'_{m1} = \frac{P}{2}\cos(\omega_{sc}t - \frac{\pi}{2})\cos(2\frac{\omega_c}{c}d) \tag{7}$$

Adding the signals and after a few simplifications we arrive at:

$$x_{out} = \frac{P}{2}\sin(\omega_{sc}t + 2\frac{\omega_c}{c}d) \tag{8}$$

Equation (8) shows clearly that the resultant signal is simply the PSK-modulated sub-carrier with a certain phase lag introduced by *d*. What is even better, there is no variation on the signal's amplitude due to *d* variation as occurred with signals x_{m1} and x_{m2} (of course, greater amplitude is to be expected if *d* is strongly reduced due to increased signal strength). Constant envelope was also achieved with this arrangement since the amplitude is not dependent on time or *d*.

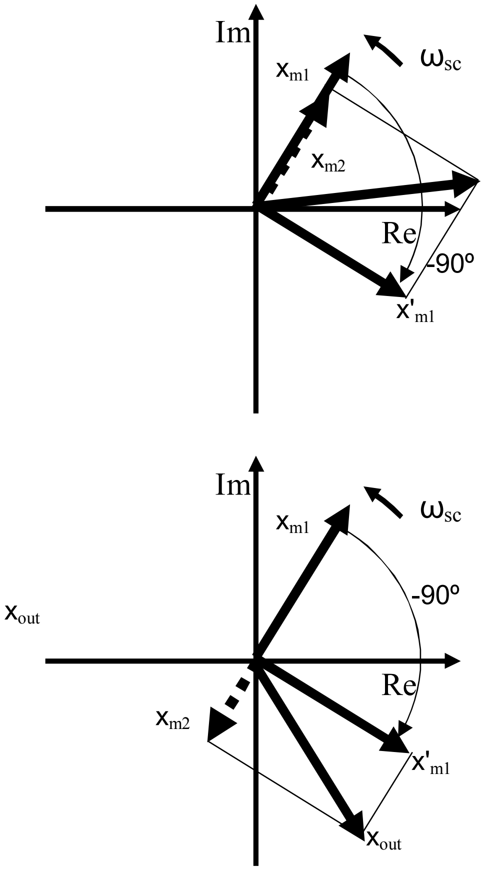

Fig. 4 - Resulting phase diagrams for the complete receiver

Looking at Fig. 5, this resembles a Hartley receiver [7]. While the structure is undoubtedly the same, the purpose is quite different. While the Hartley is a heterodyne receiver, we aimed a homodyne receiver to avoid a second oscillator. While the two-branch structure in the Hartley is meant to provide image frequency cancellation, such as the Weaver architecture [3], here two branches are needed to ensure signal detection at any distance. Moreover, Hartley architecture is aimed to SSB modulation, while in this case we are dealing with PSK modulation. A good overview about image rejection receivers, including Hartley and Weaver architectures, can be found on [8].

A possible implementation for DSRC following EN12253 [1] is depicted on Fig. 6. As is apparent, most amplifiers are tuned amplifiers: the RF front-end is tuned to 5.8GHz and the backend is tuned do the sub-carrier's frequency (1.5 or 2.0MHz, according to the sub-carrier used). The 90º degree shift at 5.8GHz can be attained with a simple piece of microstrip line a quarter of wavelength long (discrete receiver) or easily made in integrated circuit (the bandwidth reserved for DSRC at 5.8GHz is 20MHz, which we can consider very narrow band). After the down-conversion, at 1.5MHz or 2.0MHz, the 90º phase shift is easily obtainable with an all-pass filter built around an operational amplifier, for example.

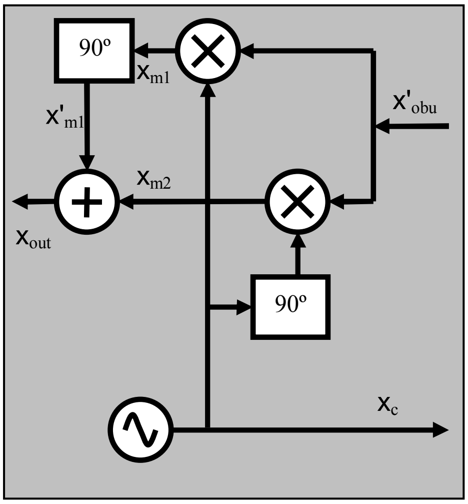

Fig. 5 - Receiver architecture

The PSK demodulator can be realized with any common technique.

One known drawback of homodyne receivers is the 1/f noise problem, since the down-converted signal has usually strong signal contents at low frequencies. This is avoided on DSRC due to the presence of the sub-carrier: the down-converted signal has its power around the sub-carrier's frequency (1.5 or 2.0 MHz). In this case, we have a homodyne receiver retaining advantages of a low-IF receiver.

IV. BEHAVIOR IN PRESENCE OF DOPPLER EFFECT

Having the OBU moving toward the RSU is a more general case. This is the common scenario at a toll paying station. We will find how Doppler affects our receiver.

Consider Fig. 7. It is assumed communication starts at a distance d_0 and the OBU is moving toward the RSU with a speed v. In these conditions, equation (4a) is slightly changed as seen on (9) to include these new parameters.

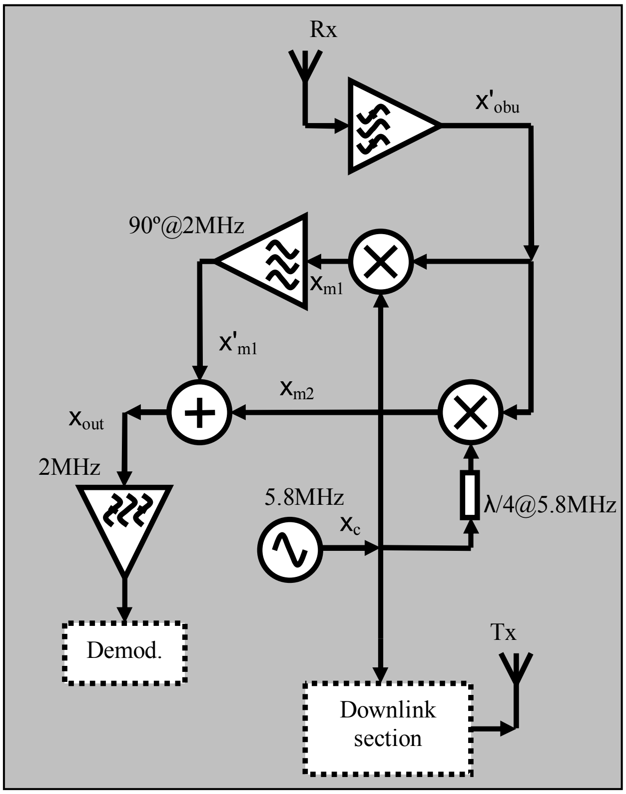

Fig. 6 - Complete receiver's block diagram

$$\begin{aligned} x'_c &= \cos(\omega_c t - \frac{\omega_c}{c} d) = \\ &= \cos\left[\omega_c t - \frac{\omega_c}{c}(d_0 - vt) \right] = \\ &= \cos[\omega'_c t - \theta_0] \end{aligned} \tag{9}$$

where

$$\omega'_c = \omega_c (1 + \frac{v}{c})$$

$$\theta_0 = \frac{\omega_c}{c} d_0$$

Clearly, the carrier frequency seen by the OBU is slightly higher (by a factor of 1+*v/c*) due to the Doppler effect. Mixing (9) with (3) results in:

$$x_{obu} = P\cos(\omega_{sc} t)\cos(\omega'_c t - \theta_0) \tag{10a}$$

or

$$\begin{aligned} x_{obu} = \frac{P}{2}\{&\cos((\omega'_c - \omega_{sc})t - \theta_0) + \\ &+ \cos((\omega'_c + \omega_{sc})t - \theta_0)\} \end{aligned} \tag{10b}$$

Once again, this signal has to travel back to the RSU. Since $\omega_{sc} << \omega_c$ we can approximate the phase delay of both frequencies to the delay of the carrier, which results in the duplication of θ_0:

$$x'_{obu} = \frac{P}{2}\left\{\cos\left((\omega''_c - \omega_{sc})t - 2\theta_0\right) + \right. \tag{11}$$

$$\left. + \cos\left((\omega''_c + \omega_{sc})t - 2\theta_0\right)\right\}$$

$$where$$

$$\omega'' = \omega_c(1 + \frac{2v}{c})$$

Mixing this signal with the carrier at the RSU and keeping only the low frequency component we get.

$$x_{m1} = \frac{P}{2}\cos(\omega_c \frac{2v}{c}t - 2\theta_0)\cos(\omega_{sc}t) \tag{12a}$$

Mixing with the carrier with a 90º phase delay results in

$$x_{m2} = \frac{P}{2}\cos(\omega_c \frac{2v}{c}t - 2\theta_0 - \frac{\pi}{2})\cos(\omega_{sc}t) \tag{12b}$$

It is now quite apparent that x_{m1} and x_{m2} are the same PSK information signal but also with a time-varying envelope due to the Doppler Effect. The envelope frequency is given by $\omega_c\, 2v/c$. Following the proposed architecture, x_{m1} is lagged by 90 degrees and summed it with x_{m2}.

$$x'_{m1} = \frac{P}{2}\cos(\omega_c \frac{v}{c}t - 2\theta_0)\cos(\omega_{sc}t - \frac{\pi}{2}) \tag{13}$$

$$x'_{out} = \frac{P}{2}\sin\left[(\omega_{sc} + \omega_c \frac{2v}{c})t - 2\theta_0\right] \tag{14}$$

Multiple aspects can be extracted from the above expression. First, it reduces to (8) when v is zero, which is in agreement with what was expected. Second, and very important, the "amplitude modulation" has disappeared, making the resulting signal a constant envelope one, unlike x_{m1} and x_{m2}. Third, a slight frequency deviation happens: the resultant PSK signal has not a ω_{sc} angular frequency as generated at the OBU, but $\omega_{sc} + \omega_c\, 2v/c$.

A little numerical example: supposing that the OBU is traveling at 200km/h (aprox. 125mph), which is a quite high speed, let the carrier's frequency be 5.8GHz and the sub-carrier's frequency be 1.5MHz. Frequency deviation due to Doppler is about $5.8\times10^9\times2\times55/3\times10^8$, i.e., 2.12kHz. This is less than 0.15% of the sub-carrier's frequency, so any demodulator is able to cope with that.

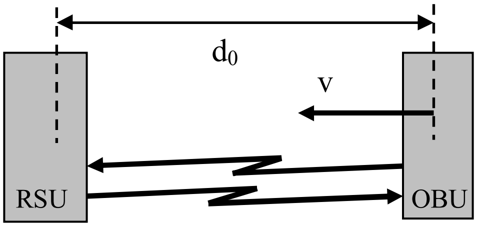

Fig. 7 - Communication with OBU in movement

V. CONCLUSIONS

The receiver architecture proposed on this paper is simple and easy to build. Since it is a homodyne receiver, there is no need for a second oscillator, IF filters and amplifiers or other circuitry needed by heterodyne receivers. On the other hand, due to the presence of a sub-carrier, the frequency spectrum is not concentrated around DC. Hence, some problems associated with homodyne receivers such as DC offsets and 1/f noise are also avoided.

A prototype around this architecture is being built and tested at Instituto de Telecomunicações.

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