Use of the GSM synchronization systems for vehicle localization services

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Abstract. *To assist the driver and to provide information about the vehicle position, it is useful to exploit the capabilities given by the cellular digital mobile communications networks.*

To provide driver assistance it is possible to use the data control traffic channels already standardized in the GSM (Global System for Mobile Communications) to carry calls or semi-automatic calls between the mobile and the traffic control station.

The paper describes the design of a digital MLSE receiver for the GSM mobile apparatus and the application of the synchronization sub-system to implement vehicle localization services using the relative time delay measurements between the vehicle and the traffic control center.

The structures for frequency estimate and symbol timing extraction also during the transmission of data packets are evaluated to support a dead reckoning system.

The localization services which can be supported by the GSM synchronization systems are not in conflict with the automatic localization given by satellite system. For example in a typical urban environment where the localization by satellite is difficult, the use of the GSM synchronism can improve the vehicle localization while in a rural environments the satellite can assure the sufficient accuracy for the localization service.

Therefore, a possible integration of the satellite and the cellular networks must be carried out in the near future.

1. INTRODUCTION

The paper proposes the use of infrastructures and of communications capability of the Pan-European cellular mobile communications system (GSM) for information calls between the mobile and the traffic control center and for vehicle localization with medium to low accuracy, 200-500 m.

The use of the cellular GSM system is justified by its high diffusion, its high number of subscribers, its reduced power: moreover simple modifications to the standard recommendations make possible to give assistance and localization services to the driver.

In the GSM standard data channel to exchange control and service operations are already expected. With respect to the problem of driver assistance the data traffic channel of the GSM system with low rate traffic < 2.4 kbit/s can be used to switch and carry out semi-automatic calls between the traffic control center and the vehicle. Therefore the traffic control center can communicate to the different vehicles the necessary information (near incident or traffic information and so on).

In the GSM radio - specifications, a synchronization system is used both in the base station (BS) and in the mobile station (MS) and the BS station continuously monitors the time delay from the MS. The delay must be assessed in such a way that the error, due to noise and interference, is less than 2 μs.

The signals sent by the BS for these purpose are:

- Frequency correction burst (FB)
- Synchronization burst (SB)

However, to locate the vehicle is necessary a more accurate measurement of the synchronism with respect to the standards and synchronization techniques must be also carried out during the transmission of the information sequences.

In the paper the Costas Loop method is used to extract from the informative packets, a reference signal which contains more accurate frequency and time information. From this signal a further correction of the frequency of local oscillator can be achieved and using a correlation method the timing delay can be compensated in a more efficient manner.

When the new synchronism on received burst are obtained the vehicle positioning procedures can be enabled.

The localization of the vehicle requires accurate measurements of the time-delay propagation of RF signals transmitted between the mobile unit and fixed stations (at least three).

The identification of the fixed stations are expected in the GSM standard and are part of the messages exchanged with the mobile, the position of fixed station can be known with reference to the road map grid but the absolute timing signals and the timing synchronization between base stations is not yet considered in the GSM system and has to be proposed to the telecommunication international committee to solve the problem of positioning.

The proposal of the use of GSM system in vehicle localization services does not necessarily lead to substitute completely the automatic localization system obtained by other system like the satellite techniques but must be lead to a possible integration of the satellite and the cellular networks in the near future.

The two integrated systems will supply the users added advantages and therefore better performance.

The following section shows the main requirements of the GSM and the features of the MLSE receiver suitable for use in the GSM system, to solve the localization problem. Section 3 describes the frequency and timing synchronization structures and Section 4 explains the necessary architectures to hold the synchronism accuracy during the data packets. Section 5 presents the main procedures necessary to implement the vehicle localization system.

2. MAIN FEATURES OF THE GSM SYSTEM AND OF THE MLSE RECEIVER TO IMPLEMENT LOCALIZATION SERVICES

The main GSM features, relevant to transmission system, are the use of a time-division multiple access (TDMA) scheme with a high bit rate R=270.83 kbits/s, and the Gaussian Minimum Shift Keying (GMSK) modulation.

The GMSK signal is a particular case of the binary Continuous Phase modulation (CPM) with modulation index h = 0.5 and BT=0.3.

The modulation can be represented, to a first approximation, as a sum of pulse amplitude modulation signals that using a derotation techniques leads to a linear form for the signal [1] [2].

The linear model can be extended to the transmission channel and to the receiving filter obtaining the following expression for the baseband received signal:

$$y(nT) = \sum_k a_{n-k}\, h_n(kT) + w(nT) \qquad (1)$$

where T is the bit period, a_k ($\pm$ 1) are the data symbols, w(nT) are the samples of an additive noise term and $h_n(t)$ is the time-varying sampled lowpass equivalent impulse response including the modulation transmission channel and receiving filter contributions.

In the GSM the propagation of the electromagnetic field between the fixed station and the mobile unit is affected by many factors, including tropospheric scattering, diffraction from natural and artificial obstacles, topographic and environmental conditions. All these factors, lead to the propagation conditions, may significantly affect the transmission quality. In particular, the signal quality can be seriously disturbed by the time - varying intersymbol interference introduced by the multipath mobile radio channel.

The simulated channel has the following impairments:

- flat Gaussian noise;
- a time-varying fading model which simulates the attenuation with a Rayleigh statistics and the Doppler frequency shift. In the simplified model with a discrete number of paths, each taps is determined by time-delays and average power selected by the COST Propagation Group as representative of urban area (TU), rural area (RA) and hilly terrain (HT).

The Maximum Likelihood Sequence Estimation (MLSE) using the Viterbi algorithm seems one of the most powerful method for compensating channels with severe distortions.

For additive independent Gaussian noise components, it is known that the MLSE criterion leads to a receiver that has to select among all possible data sequences the sequence {â} whose corresponding signal vector $\hat{S}$ is closer by Euclidean distance to the observation vector Y. In other words it selects the sequence such that minimizes

$$\| Y-\hat{S} \|^2 = \sum_{n=1}^{M} | y(nT)-\hat{s}(nT) |^2 \qquad (2)$$

where M is the length of the received samples block.

The implementation of the MLSE criterion with the Euclidean metric can be efficiently performed by the well-known Viterbi algorithm.

The MLSE digital receiver consists essentially of two blocks: the channel estimator and the Viterbi processor. The channel estimator is formed by adaptive algorithms (LMS, RLS algorithms) which supply an adaptive estimate of the equivalent channel impulse response $h_n(kT)$ apt to track the fast time-varying characteristics of the channel.

It is not necessary to enter here in further details of the MLSE receiver reported [11] as our interest is addressed to the synchronism systems necessary for the vehicle positioning.

3. SYNCHRONIZATION SYSTEM

In the GSM synchronization system, the BS sends signals on the BCCH (Broadcast Control Channel) to enable the MS to synchronize itself to the BS and if necessary correct its frequency standard to be in line with that of the BS.

The BS sends to each MS a "timing advance" parameter according to the perceived round trip propagation delay BS-MS-BS. The MS advances its timing by this amount, with the result that signals from different MS's arriving

at the BS are compensated for propagation delay.
The signals sent by the BS for these purpose are

- Frequency correction burst (FB)
- Synchronization burst (SB)

The FB is composed by fixed bits and it is equivalent to unmodulated carrier with a frequency offset of 1625/24 kHz above the nominal carrier frequency. Considering the bit rate R=270.833 kbits/s, it is corresponding at the R/4.
The frequency burst (FB) must be used to synchronize the local clock to the BS clock. Due to the communication channel model, the phase of each FB is randomly distributed. Classical phase lock loop techniques cannot be used and a modified coherent demodulation is performed with a numerical phase-locked loop (PLL).
The fig.1 shows the scheme used in the proposed receiver and in the simulations to test the frequency recovery procedure.

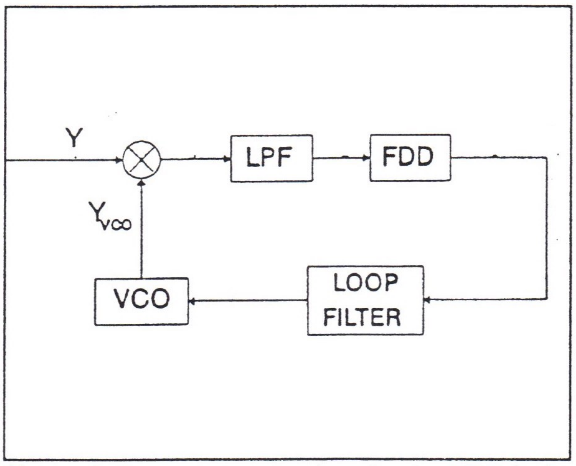

Figure 1 Frequency correction circuit - FDD is the frequency difference detector

The FB is down converted to zero frequency (phase and quadrature) to get a signed frequency error measurement of the mean instantaneous frequency within the single burst. To recover the instantaneous frequency is used an accurate algorithm which operates directly in the time domain. The received signal is given by

$$y(t) = A\cos(\omega t+\phi) \tag{3}$$

con $\omega=\omega_0+\omega_{err}$
$f_0= 2\pi/\omega_0$ is the carrier frequency
ω_{err} is the frequency error due to the shift Doppler and instability of local oscillator
Giving the in-phase and quadrature components of the signal

$$y(t)=I(t)\cos(\omega_0 t)-Q(t)\sin(\omega_0 t) \tag{4}$$

where $I(t)=A\cos(\omega_{err}t+\Phi)$ is the in phase component
$Q(t)=A\sin(\omega_{err}t+\Phi)$ is the quadrature component

an estimator of the instantaneous frequency can be the I/Q algorithm

$$\omega_{err}=\frac{I(t)Q'(t)-Q(t)I'(t)}{I^2(t)+Q^2(t)} \tag{5}$$

where I'(t) and Q'(t) indicate the derivative.
Considering discrete samples of the received signal, at one sample every T seconds, and introducing a difference equation of first order form to approximate the derivative in the above formula we obtain

$$\omega_{err}=\frac{I_{i-1}Q_i-I_iQ_{i-1}}{I_i^2+Q_i^2} \tag{6}$$

The frequency error is then averaged on subsequent bursts, (in our simulation 30 burst). The goal is to minimize the influence of Doppler effects and of multi-path propagation effects. This is correctly achieved in the performed tests on the simulated channel, where Doppler effects have zero mean, in real conditions further correction can be necessary [10].
The table 1 shows the variance of the phase locked error in the three typical areas, urban, hilly terrain and rural areas given by the GSM recommendation, and for various vehicle speed using a media of 30 burst (4440 transmitted bits).
The frequency error changes the reference clock (along with the sampling rate of the input analog signal) with a gain, which is variable with the frequency error estimate. The convergency and the stability of the clock frequency depend to the overall digital loop gain and to the digital filter: in the test performed for normal operations of GSM equalizer accuracy of more than 10^{-4} over the FB tone are been achieved.
The use of higher sampling rate are not useful for positioning purposes, while longer statistics and corrections for Doppler effects will be useful.
To recovery the symbol timing, the GSM system use as training sequence the SB. Due to its pseudo noise structure it is possible to implement a correlation method between the incoming signal and this sequence according to the following formula :

$$R_k=\sum_{n=1}^{16} SB(n)\, SB_R(n+k) \qquad (7)$$

where SB indicates the known sequence of synchronization burst and SB_R is the received synchronization burst.

The results of the computation is an estimate of the channel response.

The simulation on a media of 30 bursts shows that the error between the position of the correlation maximum on the known sequence and the position of the maximum on the received synchronization burst is about of T/N_{cb}, where N_{cb} is the number of samples/symbol used.

However in the real propagation conditions the simulation shows that the precision of the timing synchronism is better than T/4.

The FB and SB are transmitted at regular time periods. During these intervals the propagation conditions can vary very quickly and degrade the synchronism.

As the accuracy on vehicle localization depends on the synchronism precision, it is necessary to control and to hold the synchronism accuracy also during the information data packets (Normal burst NB in the GSM system) to achieve a localization of at least hundreds of meters.

Using a quadratic loop as the Costas Loop, on the received signal it is possible to obtain a reference signal which contains the necessary information of the frequency and time.

The minimization of this signal supplies the frequency deviation error and a correlation method applied to this reference signal estimates the error on the timing synchronism as shown in the next section.

3. SYNCHRONISM ON NORMAL BURST

The frequency deviation between the received signal and the signal locally generated is due to two main factors: the precision of the local oscillator and the Doppler effect due to vehicle speed, which can cause different frequencies from burst to burst.

The GSM recommendation considers the maximum frequency deviation of about 90 Hz on the 900 MHz carrier. The Doppler effect only causes a frequencies shift on the signal without change the form of the signal spectrum (the effect of the form change is in the order of 10^{-11}, a quantity under the oscillator accuracy) and the maximum Doppler shift is about of 210 Hz. Therefore a total deviation of 300 Hz can be between a burst and the next one.

Our goal is to correct the frequency and timing synchronism also during the information data packets by limiting the frequency error.

The GMSK modulation adopted in the GSM system allows the use of the Costas loop to cancel the modulation in the received signal apart during the transient from different symbols.

The Costas loop is shown in fig.2. The low pass filter only passes the component which contains the difference between the frequency of the received signal and the frequency generated by the local oscillator. The loop filter is formed by an integrator and a low pass filter which holds the frequency locked also in the presence of modulated signal.

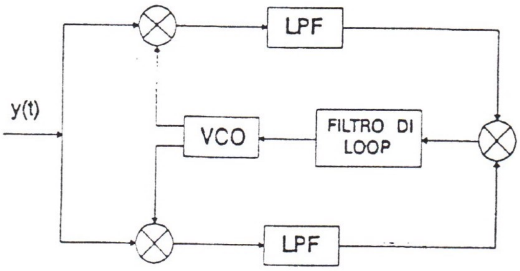

Figure 2 Costas Loop

Considering a perfect frequency synchronism the product of the quadrature components is

$$I(t)Q(t)=\frac{1}{2}\sin(\,2\phi(t)+2\,\phi_0)$$

where the term $\Phi(t)$ represents the phase modulation and Φ_0 the initial phase of the received signal. Considering a linear derotated GMSK signal [1][2], the term $2\Phi(t)$ varies of 2π rad only during the transient of the different symbols. Therefore the product I(t) Q(t) is constant apart during the transient 1 to 0 or viceversa where however has the same form, as shown in fig.3.

Assuming $\Delta\omega$ the frequency deviation due to Doppler effect or to the frequency locked error, the baseband signal y(t) can be expressed as

$$y(t)=[I(t)+jQ(t)][\cos(\Delta\,\omega t)+j\sin(\Delta\,\omega t)]=$$
$$=\cos[\Delta\,\omega t+\phi(t)+\phi_0]+j\sin[\Delta\,\omega t+\phi(t)+\phi_0]$$

$$x(t)=\Re[y(t)]\Im[y(t)]=\frac{1}{2}\sin[2\Delta\,\omega t+2\phi(t)+2\phi_0]$$

where x(t) represents the product of the real part (indicates with $\Re$) and the imaginary part ($\Im$) of y(t).

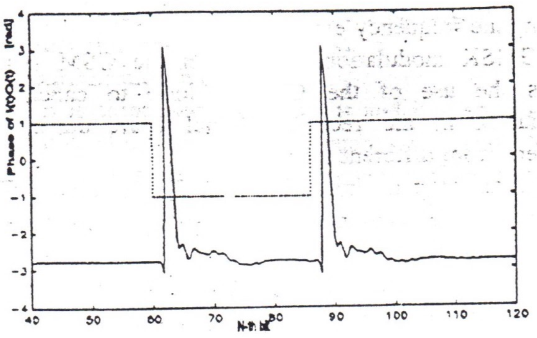

Figure 3 Phase of the product I(t) Q(t); the dash line shows the behavior of the bit; in presence of a bit change the phase varies of 2π rad.

The fig.4 shows the phase of the signal x(t) for $\Delta\omega$ =2 300 rad/s.

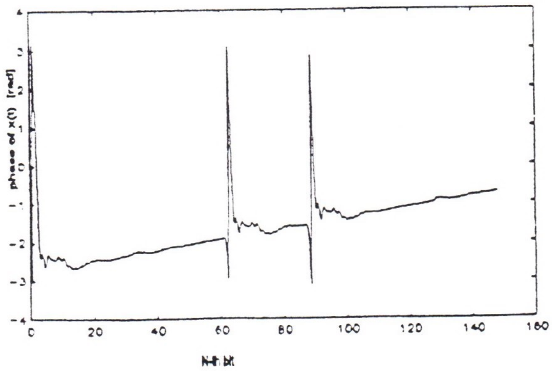

Figure 4 Phase of the signal x(t)

The Costas loop realizes a similar operation. Therefore an estimate of $\Delta\omega$ can be carried out from this method. Let us assume

$$y(t)=\cos[\Delta\omega t+\phi(t)+\phi_0]+j\sin[\Delta\omega t+\phi(t)+\phi_0]=$$

$$=I_1(t)+jQ_1(t)$$

$$2\Delta\omega t+2\phi(t)+2\phi_0=arctg\frac{2I_1(t)Q_1(t)}{I_1^2(t)-Q_1^2(t)}$$

From the above equation using a minimization technique it is possible to evaluate the linear term $\Delta\omega$. The fig. 5 shows the phase behavior along a Normal Burst and a rect which has as angular coefficient the estimate of $\Delta\omega$.

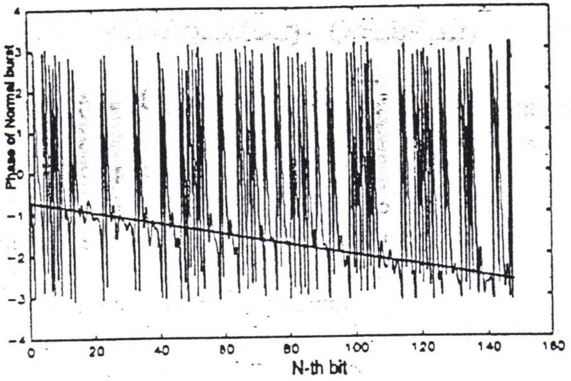

Figure 5 Estimate of the frequency error

With this method the frequency error can be corrected but it is necessary now to analyze the timing synchronism on the NB.

As shown the term $2\Phi(t)$ in the equation (10) performs a phase variation of 2π only if there is a change of bit (± 1 or viceversa), moreover when the function $2\ \Phi(t)$ rotates of 2π this is the time of the bit start.

Using the derivative function

$$\phi'(t)=\frac{d\phi(t)}{dt}$$

as in fig 6 each peak of the function represents a transient from 1 to 0 or viceversa and therefore the position of these peaks must be in the samples multiples of N_{cb} . Evaluating the position of these peaks the timing shift can be corrected.

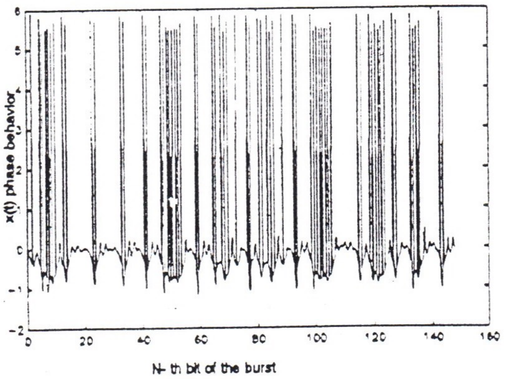

Figure 6

The timing synchronism precision on the NB does not overcome the precision obtained on the SB because only the correction determined on the SB can vary the timer of the mobile station, but it is necessary to hold this accuracy also during the NB for the positioning.

4. VEHICLE LOCALIZATION

The cover area of the base station is not uniform and the mobile can communicate with only one BS or with various BSs. Two methods for vehicle localization are analyzed: the localization by one BS and the localization by three BSs.

If it is possible to communicate with one BS can only be analyzed the distance of the MS from the BS.

Known the time of the burst transmission from the BS, and analyzing the time when the burst is received the distance measurement from the BS and the MS can be obtained. This method requires an amendment to the GSM standard to include in the burst format the information of the burst transmission time from the BS.

The maximum distance error is tied to the precision of the timing synchronism obtained on the SB

$$\Delta R_{MAX}=c\tau_{MAX}=\frac{c}{RN_{cb}}\simeq\frac{1107.7}{N_{cb}} \qquad [m]$$

If the mobile is covering a known a priori way (as a highway or a railway) or if a road map grid of the area is available the above distance measure gives the vehicle localization. The table 2 shows the values using $N_{cb}=8$ and for different typical environments.

If it is possible to communicate with at least three BSs the localization is obtained using a triangulation technique as that used in the GPS system, which test the delays measure from the BSs. This method allows also to correct the timing synchronism error from BSs and the mobile station and therefore it is possible to equip the MS with a timer with an accuracy no too high. The synchronism of the BSs timer is an optional provided in the GSM standard.

When the MS can transmit with three BSs we have three communication channels that have a different behavior at the same time. Considering all the possible combination of the delays introduced by the three channels on the vehicle positioning estimate we can obtain the results show in the Table 3.

A comparison with the GPS system highlights superior performance of the satellite system in the positioning.

The GPS system is studied specifically for the localization problem and trasnmits signals with good correlation properties to obtain an efficient time measurements. The precision is due to the availability of two codes (civil and military) which allow to investigate with an high accuracy the propagation delay of the RF signal from the satellite to the user.

The mobile positioning in the rural area or hilly terrain area carried out with the GSM system gives an accuracy shown in the Table 2 because in these areas the mobile can transmit with one BS, while the GPS system achieves performance of about 30 m.

On the contrary, in the urban area the presence of many MSs can justify the covering with different BSs and the GSM system can be efficiently used as a position system besides as a mobile cellular system. Moreover in a urban environments due to obstacles it is more difficult to receive signals from satellites and in this condition the GPS receiver can not update the positioning.

Therefore, the two integrated systems will supplied to the users unified advantages and therefore better performance.

CONCLUSIONS

GSM cellular mobile communication system appears as a promising solution to the problem of driver assistance from remote traffic control centers.

Two upgrade of the mobile apparatuses are necessary: the integration of the GSM system with the other communication, localization and routing apparatuses under the control of an intelligent processor on the vehicle; the development of the more complex numerical tasks necessary for the car positioning on the receiver.

The design of an efficient and intelligent system which make use of the various communications links on the car is yet a research problem. The upgrade of the receiver to get the time measurements necessary for the car localization must be verified with experimental tests.

The base stations are already capable to deliver the data channel services requested by the traffic control, even if no agreements exists relative to them.

The time synchronization between base stations and the implementation of timing and positioning service are not yet considered and may be subject of future proposals to the telecommunications authorities.

The proposal of the use of GSM system in the vehicle localization services does not lead to substitute the automatic localization system obtained by other systems such as the satellite but must lead to a possible integration of the satellite and the cellular networks in the near future.

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	Urban Area $E\{\omega - E\{\omega\}^2$	Rural Area $E\{\omega - E\{\omega\}^2$	Hilly Terrain $E\{\omega - E\{\omega\}^2$
v=0 Km/h	0.0016	0.0018	0.0011
v= 50 Km/h	0.0023	0.0017	0.0013
v =100 KM/h	0.0018	0.0020	0.0024
v=150 Km /h	0.0038	0.0031	0.0026
v=200 Km /h	0.0030	0.0025	0.0027
v=250 KM/h	0.0026	0.0036	0.0025

Table 1 - Variance of the frequency error

	Urban Area	Rural Area	Hilly Terrain
R_{MAX} [m]	550	346	415

Table 2 - Maximum distance for the localization by one BS

	Urban Area	Rural Area	Hilly Terrain
R_{MAX} [m]	390	86	191

Table 3 - Maximum distance for the localization by three BSs