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Research Article

Embedded Localization and Communication System Designed for Intelligent Guided Transports

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Nowadays, many embedded sensors allowing localization and communication are being developed to improve reliability, security and define new exploitation modes in intelligent guided transports. This paper presents the architecture of a new system allowing multiuser access and combining the two main functionalities: localization and high data flow communication. This system is based on cooperative coded radar using a transponder inside targets (trains, metro, etc). The sensor uses an adapted digital correlation receiver in order to detect the position, compute the distance towards the preceding vehicle, and get its status and identification. To allow multiuser access and to combine the two main functionalities, an original multiplexing method inspired from direct sequence-code division multiple access (DS-CDMA) technique and called sequential spreading spectrum technique (SSS2) is introduced. This study is focused on presenting the implementation of the computing unit according to limited resources in embedded applications. Finally, the measurement results for railway environment will be presented.

1. INTRODUCTION

Localization and communication systems become increasingly more important to ensure the common transport safety that is maritime [1, 2], airway, or terrestrial. Actually all boats and the planes are already equipped with systems based on a transponder which allows the localization and data exchange. For example, in the maritime transport domain, a system called automatic identification system (AIS) is deployed. This system equips all chips with a device using a GPS receiver to estimate the boat position and a VHF transponder to broadcast this position and other information to all chips around. However, in guided transport domain, no system is actually able to ensure these functionalities.

In the present paper, a new system, called Communication, Detection and Identification of Broken-Down Trains (CODIBDT), is proposed to optimize the exploitation mode inside automatic guided transports. Indeed, a traffic perturbation occurs when a train is broken down along the line. It is then necessary to accost [3], in safety conditions, this broken train by another train. The line is divided in parts called districts of about 1 km. When a train is in a district, it is declared to be engaged. No coach can go in until the train leaves it. This is the security system in the current networks. If the real time distance between the trains was known, the accosting phase duration between the two vehicles could be reduced significantly. This distance could be transmitted to the exploitation center, which is in charge of procedure management. This measurement should be provided in different environments where the train moves like free area, viaduct, and subway tunnel.

However, in a subway tunnel, due to the multipath reflections, a conventional radar system analyzing signal echoes on an obstacle is inefficient. In fact, as shown in Figure 1, the radar receives multiple echoes especially if an obstacle is closer than the train targeted. In such case, it is difficult to detect the right obstacle among all these echoes.

The designed cooperative radar CODIBDT overcomes these problems and its principle relies on a transponder system: transmitters and receivers equip, respectively, the front and the rear of each train. Another advantage is that it not only provides a real time distance measurement, but also allows communication with high data flow between the sensors. Then it could be helpful to develop many applications among which exchange information such as audio-video records in order, for example, to increase security feeling and

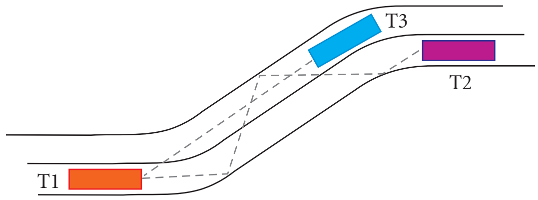
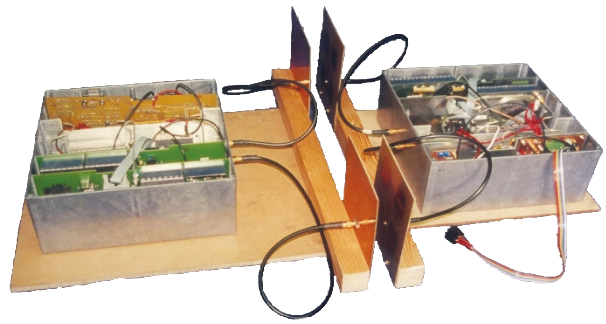
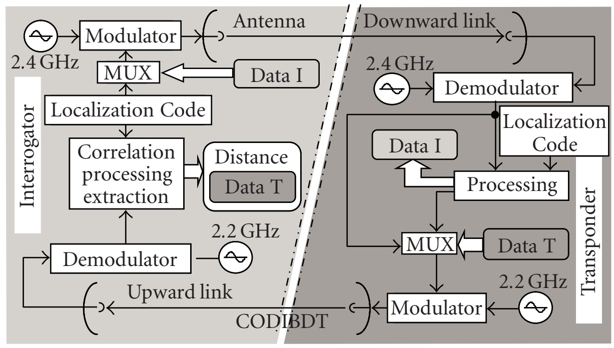


Figure 1: The problems occurred in a subway tunnel.



(a) The CODIBDT radar mock-up



(b) The CODIBDT transmitter/receiver design architecture

Figure 2

quality of service inside trains (wireless Internet). For this purpose, an appropriate multiplexing method for this sensor has been proposed to favor high data flow and robustness according to signal-to-noise ratio (SNR) criterion.

This paper is focused on developing hardware and software implementation of this system developed using flexible components such as FPGA. Finally, the results obtained with the implemented mock-up are presented in free space area and in tunnel.

2. THE PRINCIPLE OF THE PROPOSED CODIBDT SYSTEM

The implemented system has a broadband of about 100 MHz that can be used. We propose to develop a new coding algorithm to exploit this band in order to establish high data rate communications between trains and operator centers. The CODIBDT sensor is able

(i) to detect the position, get the identification and the status of the train,

(ii) to compute, in real time, the distance towards the preceding vehicle,

(iii) to allow high data rate communications for exchanging data information between trains.

Its principle relies on a transponder system using an interrogator/responder pair (see Figure 2(a)) which equips, respectively, the front and the rear of vehicle. As shown on Figure 2(b), the first vehicle (interrogator) sends a signal at a frequency of 2.2 GHz, towards the preceding vehicle (responder). This signal, which has its own radar code, is a binary pseudo random sequence (BPRS). It is received by the second vehicle ahead. The sensor of this vehicle ahead process and sends a replica of the received signal that is amplified, filtered and filled out with data at the same time. These data contain information about its identification (or identity), its working mode or state (broken-down or not, failure status), and so forth. The new signal sent at 2.4 GHz frequency is received by the interrogator that is able to deduce the intertrain distance and to recover the data sent by the responder (identification, status (broken-down or not)).

The frequency choice is an important item, because it depends on the line configuration and the possibility of resolving both effects of masking and multipath, which strongly affect the resulting signal. The present choice is settled in the range of 1–10 GHz band. For low power transmitter consumption, we choose industrial, scientific and medical (ISM) band for our sensor on (2.2 GHz and 2.4 GHz).

Such a cooperative radar system for which the target becomes active like in a transponder, the proposed system has great advantages among others.

(i) It works in each kind of environment: free space, subway tunnel or viaducts areas. In the later case, conventional radar systems based on distance measurement using signal echoes on obstacles proves inefficient.

(ii) Moreover, the pseudorandom sequence (BPRS) used, combined with a correlation receiver, are very adapted to the detection of signals over noisy communication channels and can be generated easily.

On the following paragraphs, this paper will present characteristics and performances in terms of BER and data rate of the system.

3. PRESENTATION OF THE MULTIPLEXING TECHNIQUE

This paragraph is focused on technical solutions to develop the new communication feature and optimize the combination of the two main functionalities: localization and high data rate communication. In order to provide this combination with high speed data flow, different coding methods [4] were tested and one of them is presented hereafter. Indeed,

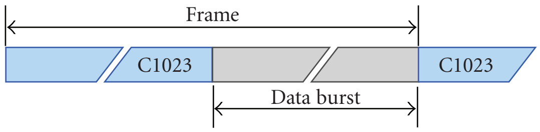


Figure 3: General structure of a frame sent with the coding technique.

Figure 4: Detailed structure of the frame sent by the SSS2 technique.

Table 1: Number of code according to register length.

Register length	3	4	5	6	7	8	9	10
Number of different orthogonal code	2	2	6	6	18	16	48	60

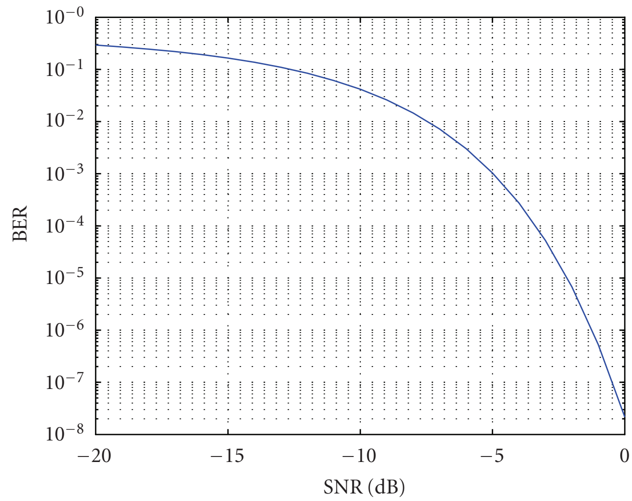


Figure 5: The BER obtained with SSS2 technique.

this method allows a continuous refreshing of the measurement of distance and also ensures a sufficient flow rate for communication with a suitable BER.

The technique is inspired from the DS-CDMA [5] and uses families of orthogonal codes (Binary Pseudo-Random Sequence—BPRS) with two different lengths. The first one has code length of 1023 bits (C1023) intended for the localization and the second is constituted by short codes of 31 bits long (C31) dedicated to the communication.

Different codes families (BPRS codes, Gold codes, Kasami codes) were studied for use in this system and were compared according to the number, the length, and the maximum of their crosscorrelation. These sequences look like a noise and so have a spread spectrum. The selected codes have the same length: 2^{n-1} [6, 7], an autocorrelation peak and a low level only for the crosscorrelation. The BPRS, also called m-sequences, presents an autocorrelation with a peak at 2^{n-1} and $a-1$ level elsewhere. They have good performances even when the signal to noise ratio is very low. Their implementation is simple. They could be easily generated using shift registers with XOR feedback. The number of these codes per family is a function of their length is presented in Table 1.

These families are considered as the reference in this study.

As we can see on Figure 3, the method consists of sending periodically the code of localization to ensure a regular renewal of the distance measurement. We propose to insert between two codes of localization a variable structure of coded data burst. Between two localization codes we insert 1023 bits, which can be divided into several short codes.

The proposed coding technique is entitled SSS2 for Sequential Spectrum Spreading using 2 codes.

The spreading with the C1023 is used to assume localization function. The second one is used to code data communications with the C31 in the classical DS-CDMA (Direct Sequence CDMA) [5, 7–9]. This technique allows us to send 33 bits of data between two codes of localization. The length of the first code is chosen to reach the required distance (about one kilometer) and due to important number of reply codes (60). The length of the second code affects the rate of communication, if we choose a shorter one, we will have a higher rate but the robustness will decrease significantly. Multiple simulations have been done and the length of 31 bits seems to be a good trade-off between the data rate and the robustness to noise. Figure 4 shows the standard structure of the frame transmitted by this method.

To calculate the distance, the correlation between the received signal and the reference codes (C1023) is computed. The correlation peak allows the synchronization process. Then, to recover data, a second correlation between the received signal and the C31 code is used.

4. PERFORMANCES

The SSS2 technique has been simulated in additive white Gaussian noise (AWGN) channel in order to evaluate its performances in terms of data flow rate and bit-error rate (BER).

On Figure 5, the bit-error rate corresponding to several signal-to-noise ratio values, obtained by simulations (with sufficient number of iterations) is given for this technique. The SNR is defined as

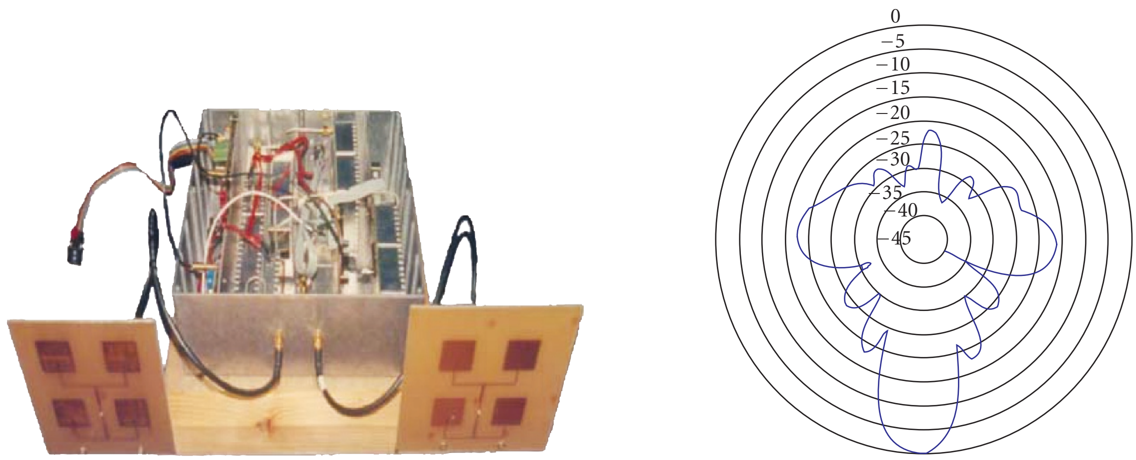
$$\text{SNR} = 10\log\left(\frac{E}{\sigma^2}\right), \tag{1}$$

where E is the maximum power transmitted by the radar and σ is the standard deviation of noise.

Simulation results show that, in AWGN channel, SSS2 technique is robust to noisy environments (i.e., SNR less than -2 dB). Moreover, a BER of 10^{-5} can be reached with SNR equals to -2 dB with this method.

Concerning the data flow rate, it could be estimated as the following:

$$\text{data flow} = \frac{\text{number of bits sent}}{\text{time}} = \frac{N}{2 * L_c/f}, \tag{2}$$



(a) The patch antenna used in our system

(b) The antenna radiation pattern

Figure 6

where N is the number of data bits sent periodically, $\mathbf{L}_c$ is the length of the localization code and f is the signal frequency.

Furthermore to ensure periodical renewal of the distance measurement, we choose to limit the data frame length to 1023 (as the localization code). And because we spread the data with a code length 31, the maximum numbers of bits which could be sent is limited to 33 bits/frame,

$$\text{data flow} \approx 1.6\,\text{Mbps}. \quad (3)$$

In this case, the data flow which could be reached is about 1.6 Mbps for a clock of 100 MHz. This data flow rate associated to the robustness of this technique in noisy environments (BER of 10^{-5} with SNR greater than -2 dB) makes this multiplexing method very interesting for our application.

Concerning the localization characteristics, it gives a resolution in distance, which is between 1.5 meter and 3 meters depending of the clock frequency used (50 MHz or 100 MHz). The maximal range obtained is about 800 meters in tunnels and 700 meters in free space.

Moreover, the radar detection is physically limited in low range, under 10 or 15 m, due to the recovery time of the sensor.

The actual laboratory mock-up integrates a multiplexing SSS2 technique using flexible components like FPGA [6] as described in Figure 6(a). We use 2 × 2 patches antennas for each link with a beam aperture of 20° to operate in curves. Figure 6(b) show the radiation pattern of each antenna.

Table 2 gives a summary of performances of the whole radar sensor.

The resolution and range in free space and tunnel are the same of about 1.5 meters for a clock frequency of 100 MHz, and we can reach 700 meters maximum range in free space and 800 meters in tunnels. The range of ours system in tunnel is greater that in free space because the behavior of the tunnel is like a "wave guide" for the frequencies used by ours system.

The preliminary results of simulations confirm the performance of the SSS2 technique (weak BER and sufficient high-speed information exchange).

Table 2: Performances of CODIBDT.

Coding	SSS2
Maximum flow	1.6 Mbps
SNR for BER = 10^{-5}	-2 dB
Range in free space	700 m
Range in subway	800 m
Resolution at 100 MHz	1.5 m
Sensor characteristics	
Antenna aperture	15°
Antenna type	2 × 2 patches
Antenna size (cm)	12 × 12

5. CODIBDT IMPLEMENTATION

5.1. Architecture choices

In order to estimate the C1023 flight time between the interrogator and the responder, a local peak is detected in the calculated cross-correlation between the received signal and the reference (C1023). To compute this correlation, the first solution is to use a conventional DSP processor. So, we have to estimate the number of operations needed per second. Indeed, the maximum frequency of the transmitted signal is about 50 MHz (or 100 MHz) and the received signal has to be sampled at least twice per chip. So, the signal to be processed has a given rythm of about 100 MHz (or 200 MHz) and for each chip, at least 1023 MAC (Multiplication and accumulation) are needed to calculate the intercorrelation. Due to the fact that DSP processors carry out a MAC operation by clock edge, a processor which runs up to 102.3 GHz or (204.6 GHz) is required. However, such a processor does not exist on the market yet. For these reasons, we mother choose new generation components such as FPGA which propose a more flexible and easily reconfigurable structure and where treatments may be massively parallelized.

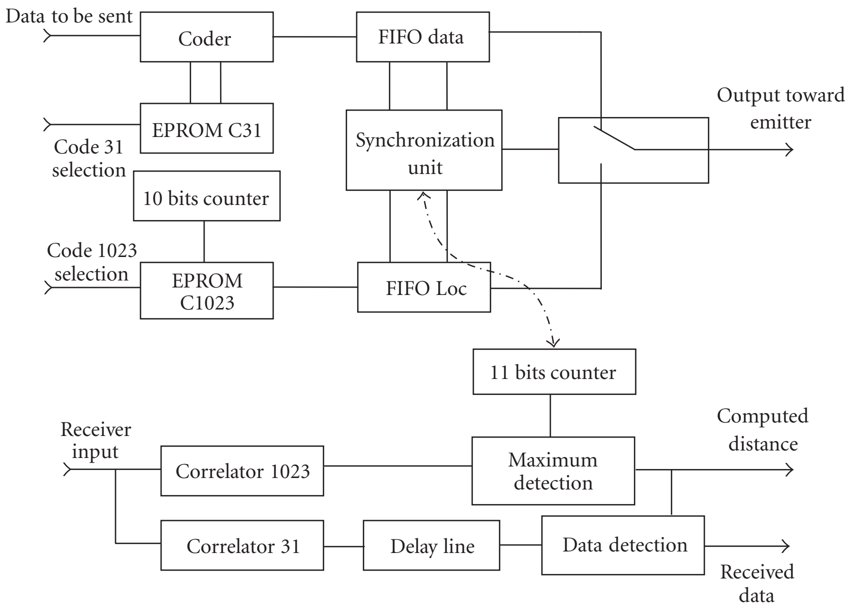


Figure 7: Different modules implemented in the FPGA component of the interrogator.

So the computing unit needed for calculating the correlation as well as the detection unit will be implemented on FPGA components. The correlation unit is composed by a barrel of parallel multipliers and accumulators. Thus, the system can run as fast as the frequency of the received signal (i.e., in real time). Moreover the detection unit is programmed such a "state machine." In our design the biggest element, which consumes the largest resources of the FPGA, is the correlator module. Multiple architectures to implement this module is developed to optimize the resources consumption according to limitation imposed by the specification or the embedded applications.

5.2. Global implementation of the CODIBDT process

As shown on the previous paragraphs, the proposed system is made of a couple of microwave transmitting and receiving equipments fixed on each train (resp., interrogator and responder). The transmitting equipment includes a modulator and a demodulator, respectively, at 2.2 GHz and 2.4 GHz frequencies and includes also a computing unit composed by an ADC—analogue-to-digital converter—and FPGA device. The receiving equipment is similar but the modulator will run at 2.4 GHz and the demodulator at 2.2 GHz. The localization-communication procedure will be made in several successive steps, which can be summarized as follows.

The interrogator will build the global frame and send it towards the responder at 2.2 GHz.

The responder demodulates the signal at 2.2 GHz and identifies the localization frame, then it replaces the interrogator data frame by his data frame.

The new global frame will be sent to the interrogator at 2.4 GHz.

Besides the interrogator, the computing unit will calculate the correlation between the received signal and the different code (C1023 and C31) in order to estimate the fly time and decode the data frame.

The working of the computing unit will now be described.

5.3. The interrogator computing unit

As shown in Figure 7, the interrogator computing unit can be divided into two principal blocks: the transmitting block (at the top of the figure), and the receiving block (at the bottom). It has different inputs and outputs such as

(i) data input,
(ii) C31 and C1023 code selection,
(iii) received signal which is plugged into the ADC output,
(iv) signal output,
(v) estimated distance and received data output.

It contains different modules as the following.

(i) EPROM's where the two different BPRS codes used are stored.
(ii) Coder module: to spread the data with data code.
(iii) Data FIFO where spreaded data will be stored.
(iv) FIFO Loc where localization code will be copied.
(v) Synchronization unit which builds the global frame by synchronizing the read operation for the two FIFOs.
(vi) Some counters: 10 bits counter to transfer the localization code from EPROM to FIFO loc, and 11 bits counter used as a time references (reference counter).
(vii) Two correlators.

(viii) Peak detection to detect the peak present in the correlation result between the received signal and the localization code.
(ix) Data detection.

The communication localization process will start in the interrogator FPGA by constructing the burst to be sent. The coder component will modulates the C31 code stored in the EPROM and put it in "FIFO Data" and the 10 bits counter transfer the C1023 stored in the EPROM into the "FIFO Loc."

When the reference counter is reset to zero, the synchronization unit deals with orchestrating the sending of the localization code present in "FIFO LOC;" followed by 33×C31 codes modulated by the data present in the "FIFO data."

This signal will be received by the responder and will be amplified, modified and sent back towards the interrogator.

Besides the interrogator the module "correlator 1023" calculates the intercorrelation between the received signal and reference code C1023 and in the same time the "correlator 31" module calculates an intercorrelation between this signal and reference code C31.

When "maximum detection" module detects a peak in the correlation results with C1023, the value present in the "11 bits counter" is raised up. This value represents the flight time of the radar signal. Then the reception of the data is performed also, by estimating the sign of the correlation result with code C31. The "delay line" module is used to synchronize the results of both correlators; because there are different response times of about 10 chips and 5 chips.

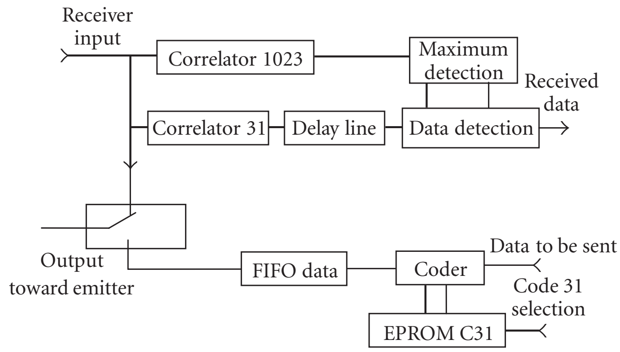


Figure 8: Different modules implemented in the FPGA component of the interrogator.

Figure 9: Measurement made in the tunnel using the realized mock-up.

5.4. *The responder computing unit*

Besides the responder, to ensure the function of localization, a copy of the received signal is sent back to the interrogator. And in order to exchange data, we exploit the C1023 code sent by the interrogator to synchronize the two components. To ensure that, we compute an intercorrelation between the received signal and code C1023. The detection unit algorithm will take care to detect a local maximum in a guard interval. The presence of one peak indicates that a data frame is being sent. Once the synchronization peak is detected, the sign corresponding to the second correlator peak will be estimated. If the transponder has some data to transmit, we wait until a C1023 peak is detected; then, instead of sending a copy of the received signal, the transponder will send the package of modulated C31 present in the "FIFO data."

At the first interrogator stage, the correlation function is calculated using the C1023 code (Figure 8). The peak position determines the distance and the synchronization for the data frame. At the second stage, a second correlation is calculated with the C31 code to detect data information as by the DS-CDMA decoding technique.

6. EXPERIMENTAL RESULTS

Some trials have been carried out with the preliminary mock-up in real life conditions to evaluate the localization and the communication functions. The measurements have been made in the different environments the radar maybe used. Figure 9 shows the mock up placed in the front of the vehicles.

An example of the received signal from the transponder located 100 meters far from the interrogator is shown on Figure 10.

We can note on this graph that there are many interferences with other systems working in the same frequency band, that is, 2.2 GHz to 2.4 GHz.

The architecture of this radar is efficient in these conditions and avoids the interference effects. In fact, Figure 11 shows the performances of the correlation tools associated to BPRS codes. The corresponding peaks could be easily detected.

Figure 12 presents a zoom on the first 4000 samples of the signal shown on Figure 10. It corresponds to a signal processed with a signal analyzer using an oversampling ratio of about 40. The signal has a rythm of about 50 MHz. The intrinsic central processing unit includes two ADC that can work at 100 megasamples per second. An oversampling ratio of about 2 or 4 could there be reached.

On Figure 13, the normalized intercorrelation result of the received signal with the code C1023 is presented together to the time reference. The delay time between the two signals corresponds to the flight time relative to the distance.

On Figures 14 and 15, the result obtained after the correlation between the received signal and the localization code

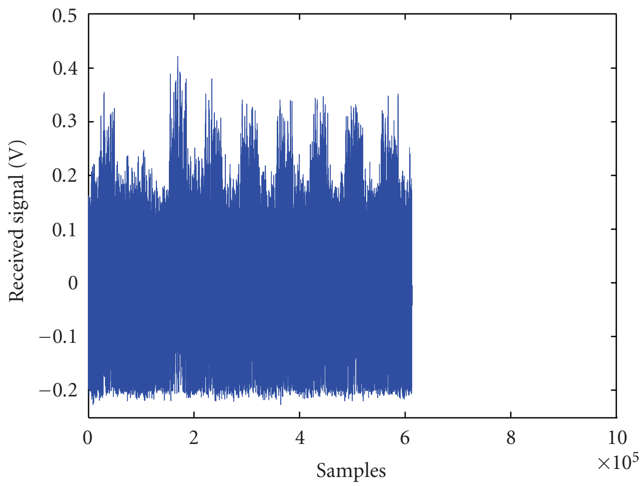


Figure 10: Received signal target at 100 meters.

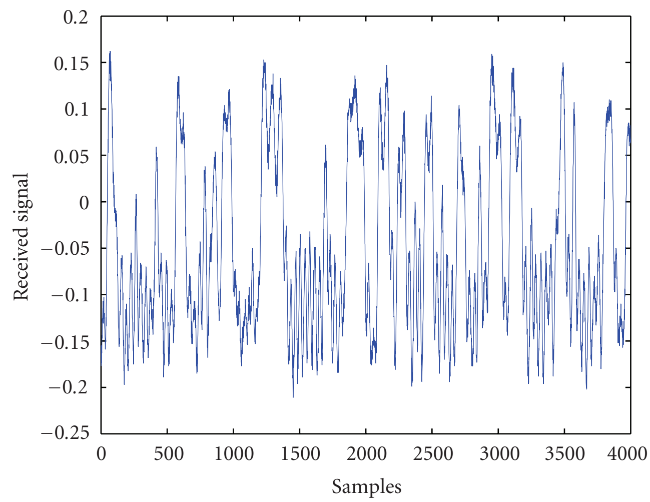


Figure 12: Received signal zoom first 4000 samples.

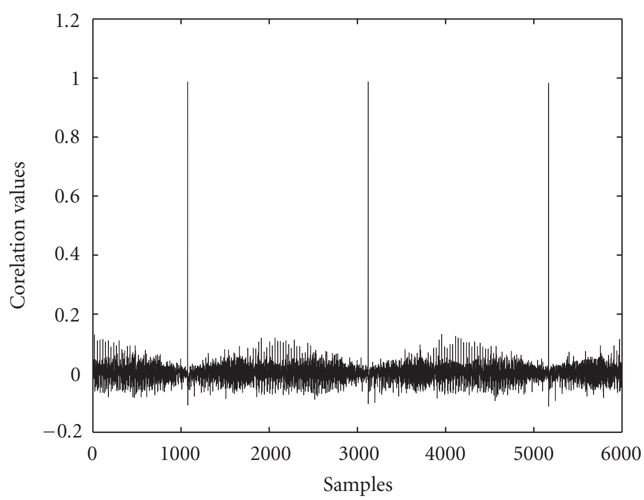


Figure 11: Correlation result with C1023.

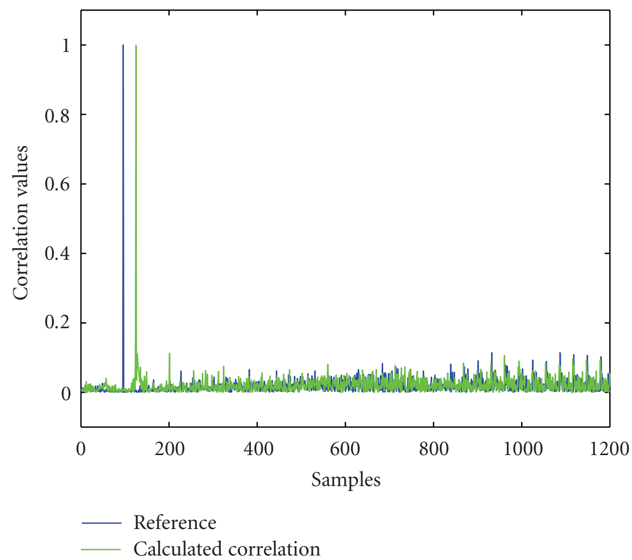


Figure 13: Correlation result with C1023.

C1023 (black color) and data code C31 (gray color) are represented.

We can see on Figure 14 that, between two localization codes, a series of data sent could be extracted easily. Moreover, on Figure 15, the data peaks are periodically distributed spaced of 31 chips. Between the localization peak and the first data peak, only a 26 chips delay exists (instead of 31) due to the difference in response times between localization correlation and data correlation. This difference, as we mentioned previously, is about 5 chips.

7. CONCLUSION

In this paper, new cooperative radar dedicated to automatic guided trains is presented. This sensor allows two functionalities: localization and high data flow communication. To combine these functionalities, original multiplexing methods called SSS2 have been proposed. This technique is inspired from CDMA base and uses successively two coding frames to ensure the multiplexing between the localization and the communication part and at the same time to give automatically multiuser access. With this method, the CODIBDT sensor achieves interesting performances in terms of localization range that is about of 800 m in subway tunnel and 700 m in open space with resolution of 1.5 m. However, the communication between vehicles is established with flow data rate up to 1.6 Mbits/s.

Many simulations have been computed to look further the system's performance in terms of computing time and complexity. And in order to validate simulations results, a mock-up have been build outfitted with flexible component like FPGA devices. This FPGA device contains the computing

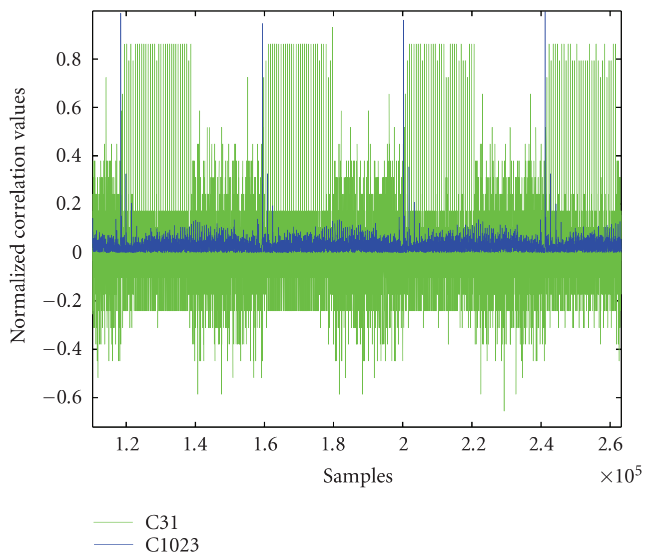


Figure 14: Correlation result with C1023 (black) and C31 (gray).

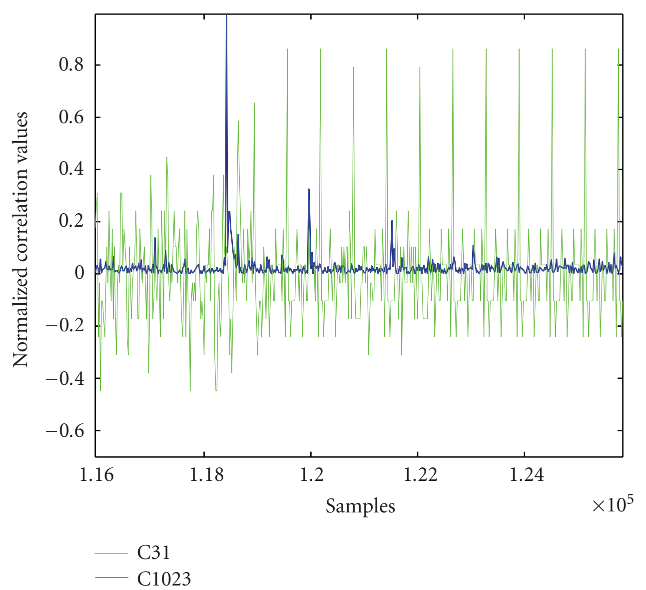


Figure 15: Correlation result with C1023 (black) and C31 (gray) zoom of Figure 14.

unit of the whole system (interrogator and responder) including also the coding technique and the detection algorithm. Future works will be oriented to multiplexing technique enhancement. Higher data flow rates could be reached by the same system using other coding method. Simulations of these methods will be performed with real channel model corresponding to free area and tunnel.

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