Precise TDMA Frame Synchronization Using DCF77 for a Short Range Mobile Radio Network

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Abstract

A frame/slot synchronization protocol called ESDA (External Synchronization with Decentral Adjustment) to support real time oriented TDMA channel switched medium access for short range mobile radio networks (SR-MRN) is described. This protocol is based on an external time signal of the radio clock DCF77 and decentralized synchronization algorithms. This time signal is used as a global time reference to establish local frame and slot synchronism of mobile stations communicating via a TDMA radio network. Decentralized synchronization algorithms are used to adjust the synchronization time point determined by the global time reference of the radio clock to achieve the required precision.

In the application considered accuracy of synchronization must be up to some microseconds to guarantee the efficient use of channel capacity, because of the requirement of broadband transmission (about 1Mbit/s) and relative short slot duration (some hundred microseconds). Since a limited transmission range below 1 km will be considered for the SR-MRN, only local synchronism covering mobile stations being in their respective interference range is necessary.

The frame/slot synchronization protocol EDSA and the application of the radio clock DCF77 signal is defined. An experiment, performed on a test platform developed for the purpose of receiving the reference signal with high quality and low cost in mobile environment is introduced. Decentrally operating synchronization algorithms are shortly described and performances of this protocol in comparison with a totally decentralized synchronization algorithm are shown finally.

1 Introduction

The short range mobile radio network (SR-MRN) is characterized by its ability to support continuous and real time data communication between vehicles and with roadside infrustructure. Reliable transmission channels are required in this application. Medium access control protocols [4] [10], based on a slotted and framed TDMA structure and channel switched communication techniques are proposed. To support reliable operation of these medium access protocols and to avoid time overlapping of communicating mobile stations, a precise frame and slot synchronization protocol is required.

Because of the requirement of broadband transmission (about 1Mbit/s) and relative short slot duration (some hundred microseconds), the required accuracy of synchronization have to be in the range of microseconds to guarantee the efficient use of channel capacity. Carrier frequency at GHz range will be used for the SR-MRN and the corresponding transmission range below 1 km will be considered. Thereby only local synchronism covering mobile stations (vehicles) being in their respective interference range is necessary.

Since mobile stations using SR-MRN services are assumed to be distributed all over Europe, an appropriate global synchronization signal distributed from a central transmitter appears to be advantageous. The GPS satellite system can provide a time reference signal with a very high precision in ns range all over the world, but it requires a high cost receiver and is therefore not suitable for such kind of commercial application. A low cost alternative is to use the low precision time signal of a radio clock and then to adjust global time reference using decentral algorithm for the desired precision. This is the idea we are going to deal with in the next sections.

Several decentral operated synchronization algorithms [7] [8], based on autonomously selected synchronization timing without any external reference signal, are also proposed for the application in the SR-MRN. Such methods, however, have a common and unavoidable disadvantage: in case of merging or crossing of two or more clusters of stations, having different synchronization time points (which is the normal case), poor performance like degradation of throughput and increasing time delay will result. This can be observed clearly in the presented results.

In the following sections we first introduce the ESDA synchronization protocol with the application of the radio clock DCF77 as a global time reference. And then the experiment, performed on a test platform developed to receive the DCF77 signal with high quality and low cost in a mobile environment, as well as the measured results about the accuracy of the generated synchronization signal are explained. In the fourth section we describe the proposed synchronization algorithms shortly, and the results of performance evaluation of the protocol, compared with a totally decentralized synchronization algorithm are presented finally.

2 ESDA Protocol with the Application of DCF77

The local frame and slot synchronization protocol ESDA (External Synchronization with Decentral Adjustment) is based on an external global time reference and a decentral operated adjustment algorithm in each station to achieve the required precision. This protocol uses a cheap equipment to receive the external time signal transmitted by the radio clock transmitter DCF77 and generates, by means of a receiver, one impuls per second as global synchronization time reference. Because of the narrow band transmission characteristics of this radio clock signal, the reachable accuracy is only 0.5 ms [6]. Two decentralized synchronization algorithms, based on Averaging the Synchronization Differences (ASD) of neighbouring stations, and Correction of synchronization according to Subjective Opinions (CSO), are developed to achiev the required synchronization precision in microsecond range. This protocol also avoids the above mentioned disadvantage of performance degradation resulting from totally decentralize operated synchronization algorithms. The application of the radio clock DCF77 as well as the slot and frame structure is explained in this section.

Because of the long wave characteristic of the 77.5 kHz signal and thereby the large transmission range of the space wave, the transmitter is suitable as a global time reference distributor for the application of SR-MRN for covering the service range of the whole Europe.

This radio clock transmits an amplitude modulated digital signal at a highly stable ($10^{-12}/day$) carrier frequency of 77.5 kHz. At the beginning of each second (except the 59 th second, the mark of a minute) the carrier amplitude drops to about 25% with a duration of either 100 ms or 200 ms, which represent the logical zero and the logical one, whereby time is coded in minutes, hours, days and so on. Detailed description about this radio clock transmitter can be found in [6].

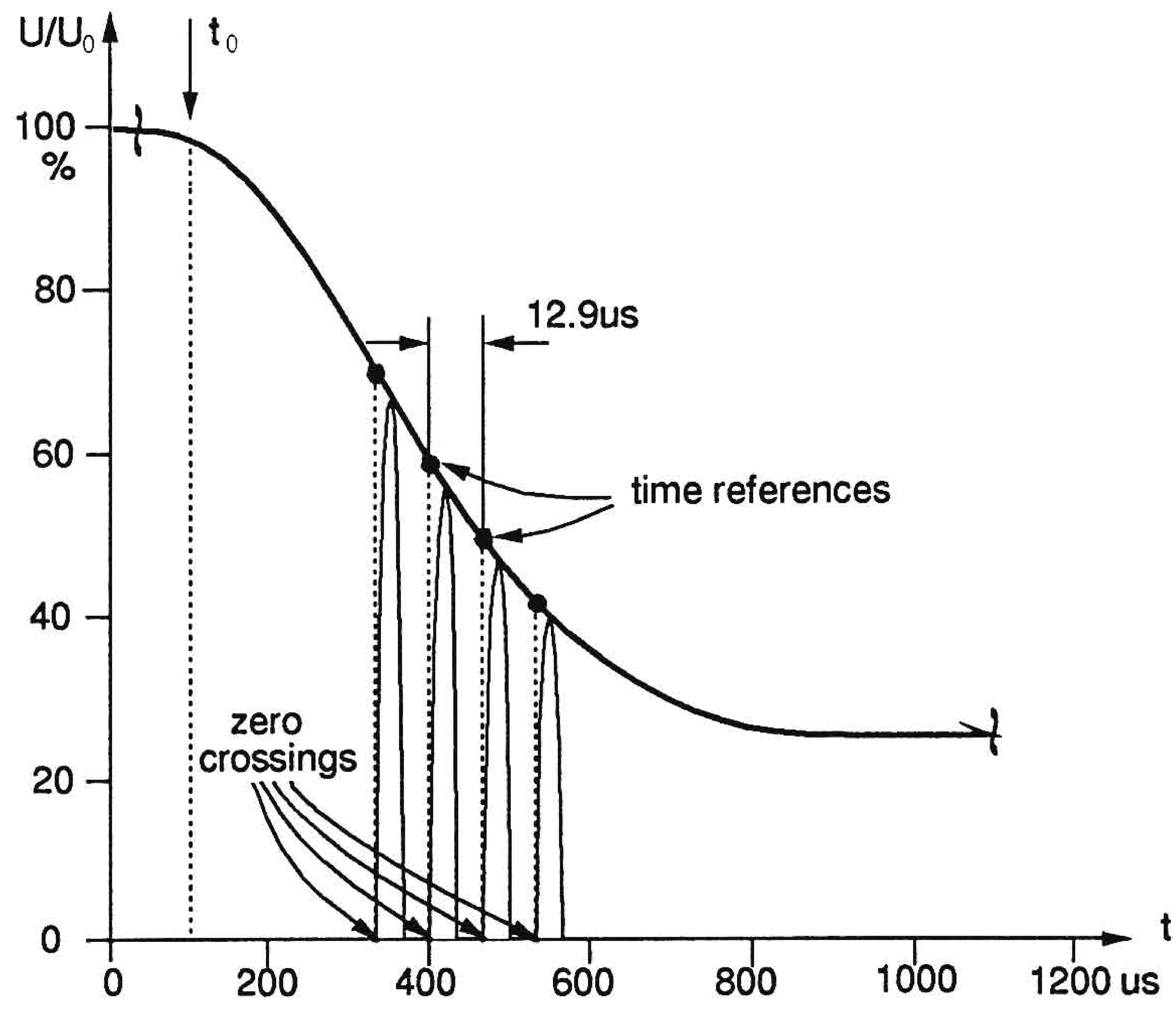

Figure 1: The shoulder of the radio clock signal DCF77

The falling shoulder of the carrier signal at the beginning of each second is interesting for us (shown in Fig. 1), which is used as external global synchronization reference for all mobile stations. Because of the duration of a falling shoulder of about 0.5 to 1 milisecond, the shoulder is devided into 38 to 77 discrete time points marking the positive zero crossings of the 77.5 kHz carrier signal (see also Fig. 1). Because of the above mentioned high stability of the carrier frequency these positive zero crossings are proposed to be used for the synchronization purpose of mobile stations in our synchronization protocol, in which each station is equipped with a DCF77 receiver and selects independently from each other one of these discrete time points (not anyone but the optimal one, which is positioned near the 70% to 80% of each falling shoulder, see also next section), when the receiver is switched on. This selected time point is used for each mobile station as its subjective global time reference.

Once a zero crossing is selected as reference time point by a station, this zero crossing, instead of the absolute time point, at which the zero crossing is selected, should be kept hold by the station, whereever the station moves to. So that the local global synchronization can be achieved, even stations move near to each other, which have selected their own time references at different places far away from each other.

This can be realized because the falling shoulder can be received theoretically every second. The related maximal time drift within this time duration is only 0.16 μs, if we assume that the maximum vehicle speed is about 180 km/h. This time drift is significantly smaller than the time period of zero crossings. This means the selected time point can be kept hold inspite of position change of mobile stations.

Each mobile station, after receiving the contents of a data burst from its neighbour, can identify the reference time point of its neighbour stations, since the propagation delay within the limited transmission range of GHz carrier frequency is significantly smaller than the zero crossing period of the DCF77 carrier signal (12.9μs).

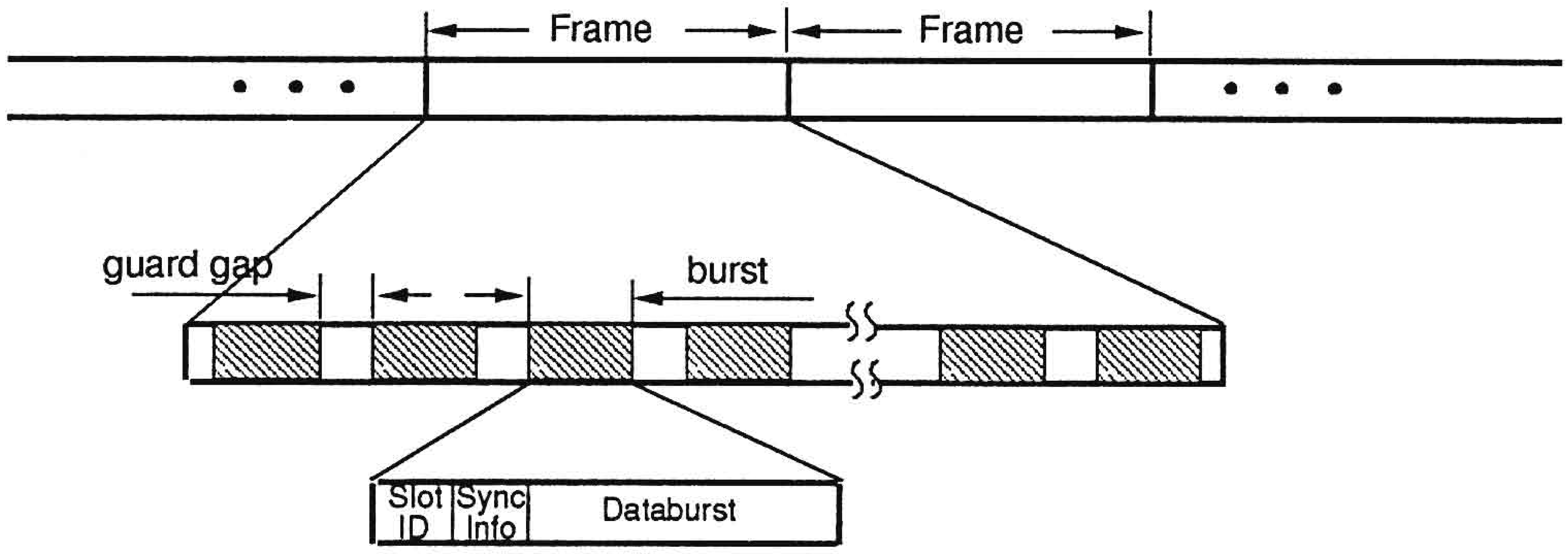

Figure 2: Frame and slot structure

This proposed global synchronization can be used for slot as well as for frame synchronization, dependent on the requirement of the logical link layer, to support TDMA medium access protocols. Fig. 2 presents the frame and slot structure. If all stations can synchronize exactly at the same zero crossing point, the maximum guard gap need be only 6.6 μs to overcome the asynchronity resulting from propagation delay, which is related to the propagation delay of the DCF77 signal between the transmitter and the receiver (maximum 3.3 μs) as well as the propagation delay of a burst transmission (maximum 3.3 μs). An enlargement of the guard gap by multiplying of 12.9 μs is necessary, if stations cannot be synchronized at the same zero crossing point.

The slot identification (SlotID) has to be transmitted implicitly in each burst, if a frame synchronized medium access is required. After receiving the contents of a burst in a frame the receiver can identify the frame beginning of the transmitter according to the SlotID. Otherwise (for the slot synchronization for instance) the SlotID has not to be transmitted at the beginning of each burst.

In the field of SyncInfo the information related to the synchronization, e.g. number of neighbours, number of received bursts in last frame, the priority of the current synchronization point and etc. can be transmitted. The amount of information transmitted in this field is dependent on the applied synchronization algorithm, which adjusts the global synchronization to achieve the required accuracy. The suggested synchronization algorithms are described in section 4.

3 Experiment of DCF77 Receiver and Its Results

Reports on stationary receive behaviours of the DCF77 from different distances with various receive conditions can be found in [5] and [1]. Our experimental equipment is constructed and used for the following purposes:

- to prove the useability of the radio clock signal for the application considered
- to receive the reference signal with high quality and low cost in a mobile environment, and
- to evaluate the statistical behaviour of the synchronization points selected by stations according to the mechanisms described in section 2.

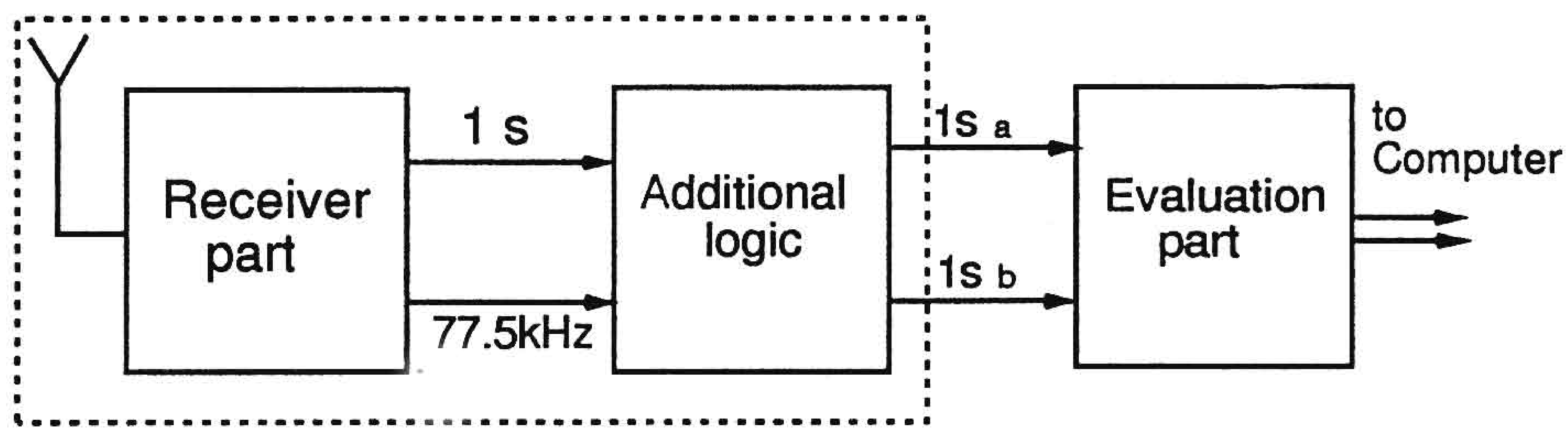

Figure 3: DCF77 experiment setup

As shown in Fig. 3 the equipment consists of three seperate parts, namely receiver part, additional logic and evaluation part. These three parts are constructed specially for the mobile environment. They are small in size, compact in form, need small amount of energy and are not interference sensitive. In the following the functionality of each part of this equipment is introduced shortly. The detailed description can be found in [3] and [2].

Fig. 4 shows the function block of the DCF77 straight-circuit receiver, which was used due to its simplicity. The use of a micro controller is still not considered in this implementation. The straight-circuit receiver is equipped with a small rod antenna being

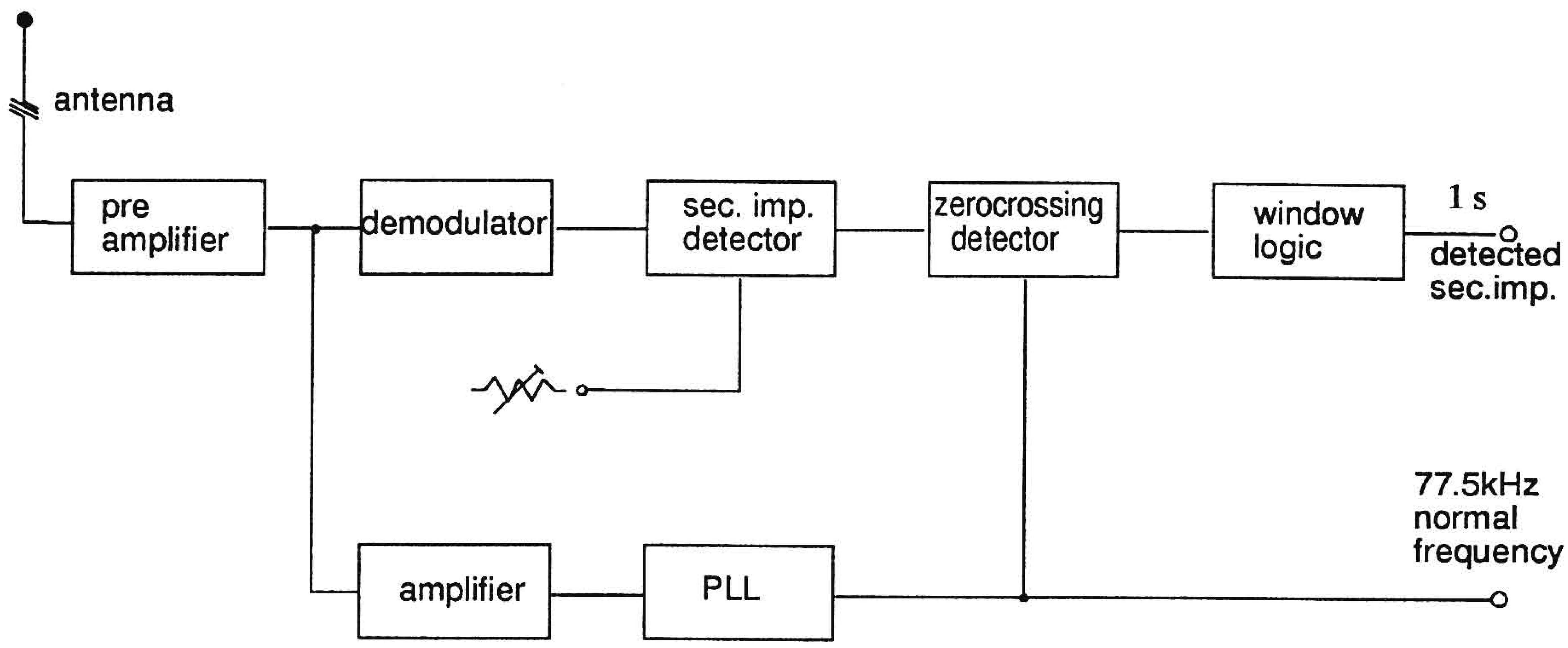

Figure 4: Function block of the straight-circuit receiver

suitable for the mobile environment. The trigger point is selected at about 70% to 80% of the carrier amplitude on the falling shoulder of the DCF77 signal at beginning of each second, because on one side the steepness of the flank at above range is the largest, and on another side the change of the falling shoulder at a higher trigger point is less noticeable as a lower one [5]. The signal from the demodulator is compared with the reference amplitude in the second impulse detector. The normal frequency of 77.5 kHz is amplified and stabilized in the PLL. If a positive zero crossing is detected immediately after the trigger point, a second impulse will be generated by the zero crossing detector. The window logic is constructed to avoid the undesirable impulses resulting from interference in the mobile environment. This generated second impulse from the receiver part is used as the subjective selected synchronization point for the station equipped with this DCF77 receiver.

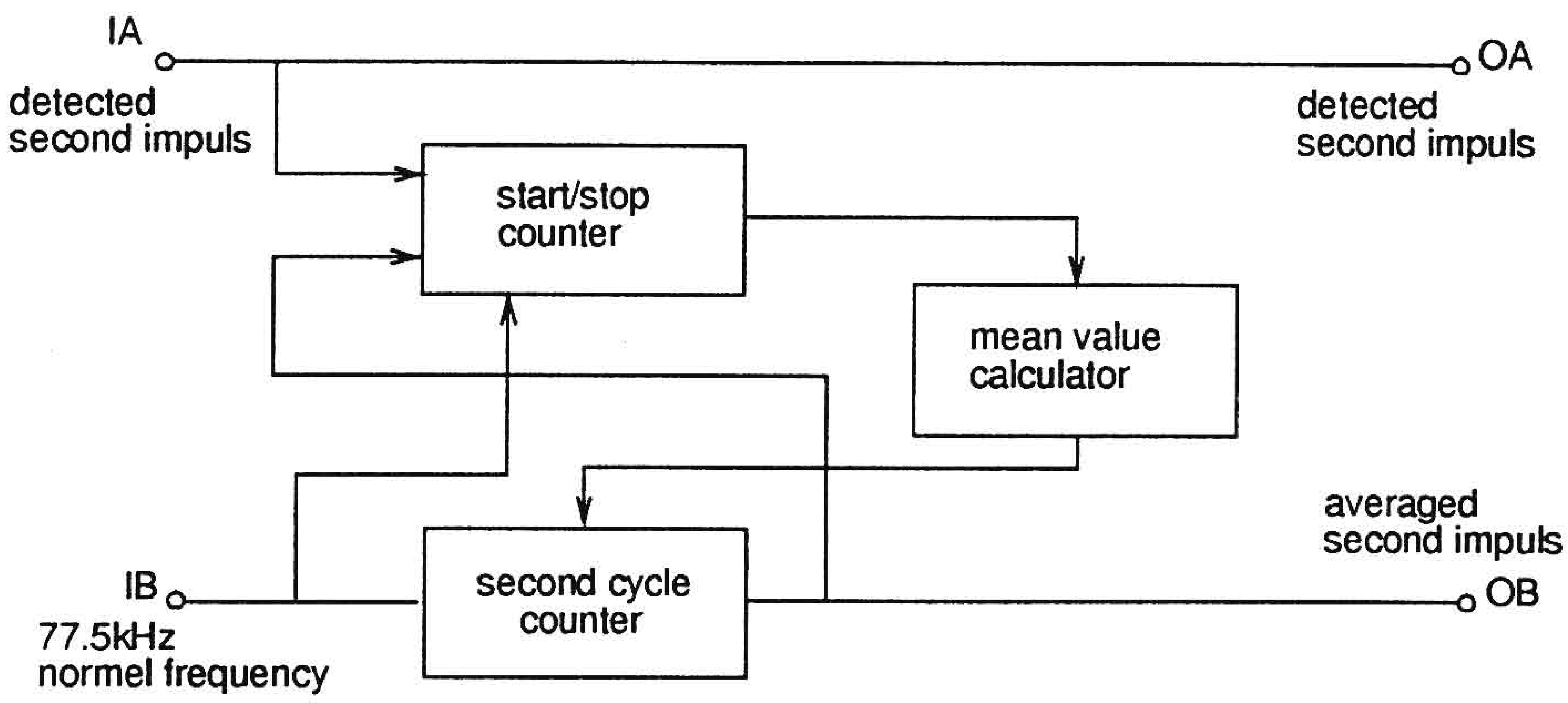

Figure 5: Function block of the additional logic part

Considering overlapping behaviour of space and earth waves in a range with a distance of 700 km to 1100 km from the DCF77 transmitter, the signal amplitude can suddenly drop and the signal phase can be shifted. Additionally, if a vehicle is driven into a tunnel or in some other extreme situations, the DCF77 signal could be lost for the receiver. In these cases the accuracy of the generated second impulses will be dramatically disturbed. To overcome these situations we use an additional logic to average the time deviations of neighbouring second impulses, and to calculate a mean deviation. The principle of the additional logic is shown in Fig. 5. The start/stop counter is started by the first entering impulse and stopped by the second entering impulse. These counted values are added and averaged in the mean value calculator. In the second cycle counter a second impulse will be generated after 77500 periods of the normal frequency are counted. The generated second impulse is corrected by additional logic according to this calculated mean deviation, so that the accuracy of the time reference will be improved.

The evaluation part is an absolute time reference with an accuracy of about 0.5ppm. This part is constructed for the measurement of the accuracy of the second impulses transmitted from the receiver part or from the additional logic part. The measured data are stored to a memory for further statistic analysis. The evaluation part operates continously and undisturbed by power switch on and off during the measurement in the mobile environment.

Fig. 6 presents the latest results of this experiment. It is a 14 hour measurement in a mobile environment and about fifty thousand measured data (one in each second) are presented in this figure. This experiment is carried out with an small car (Peugeot 205) equipped with the equipment described above (all three parts). The drive route is from Aachen (Germany) to Calais (France) and then back to Aachen, which have the distances of 200 km and 500 km, respectively, from the transmission place (Mainflingen).

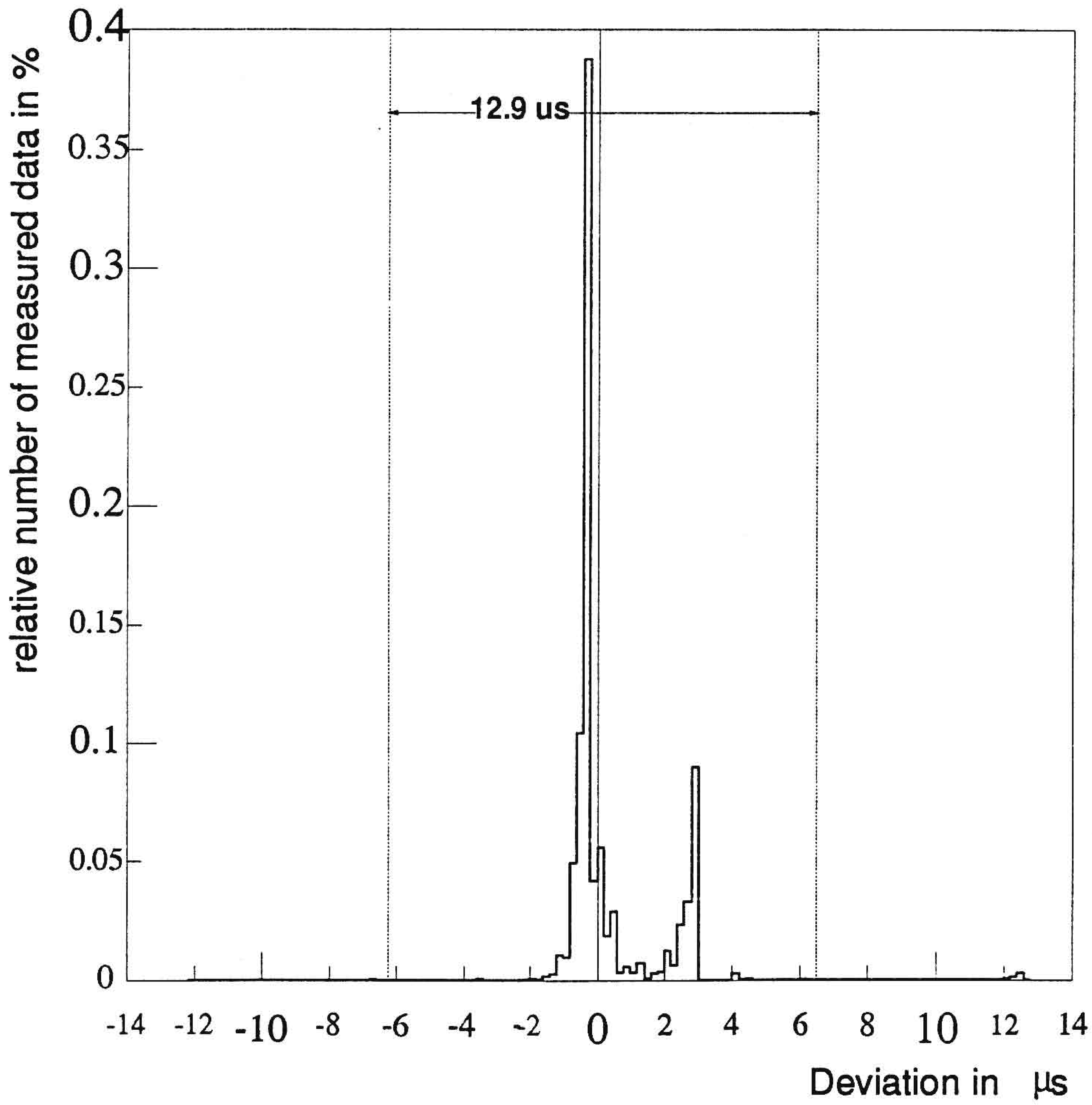

Figure 6: Results of the experiment

The measured data are the time durations between every two neighbouring second impulses, The X-axis denotes the results of the time deviations of the measured data from 1 second. The Y-axis presents the amount of measured data. Two dashed lines present the time distance between two neighbouring zero crossings, which is 12.9 microseconds. It is obvious from the figure, that the time deviation of all measured data is very small, about $\pm$ 2 microseconds, and 40% measured data are concentrated in a very small time area about 200 nanosecond. The probability that another zero crossing is selected is extremly small (see the small amount of data at the 12 to 13 microsecond area on the X-axis). The small amount of data, which lie 2 to 3 microseconds apart from 1 second, are obviously not expected, the reasons of this is still to be found.

Through the analysis of the results we can say that the DCF77 receiver can conserve definitively one selected zero crossing, whereever the station moves to, on which the receiver is mounted.

It must be mentioned that the experiment is carried out with a single receiver. The time deviation of the subjective selected zero crossings between mobile stations is impossible to be statistically evaluated in this experiment.

4 Decentral Adjustment with Synchronization Algorithms

It is proposed that each station is equipped with a DCF77 reference signal receiver, as described above, and is able to select an "optimal" zero crossing point on the falling shoulder of each second as its reference synchronization point. Since the reachable accuracy through DCF77 signal only cannot accomplish the requirement as mentioned before, decentral operated synchronization algorithms are developed to adjust the reference synchronization point to achieve the required accuracy. The following goals have to be achieved through the adjustment of the individually selected global time reference points, which are assumed to be normally distributed, by these algorithms:

- Local synchronization (synchronization between neighbouring stations) should be reached rapidly to support reliable channel switched communication between mobile stations being in their respective receive range.
- If two or more clusters of mobile stations, which have had no radio contact to each other, merge with each other, the synchronization deviation between different clusters should be within a tolerable time range, so that the existing communication channels of different clusters can be used without loss of quality caused by interruption and interference of unsynchronized, thereby overlapped communication.

Two synchronization algorithms are introduced, both of them adjust the global time reference to the possible "optimal" one, so that time differences between neighbouring stations lie within a small tolerable range, which can be realized by the guard gap between each data burst.

Algorithm ASD

The first algorithm ASD is based on Averaging Synchronization Differences between its reference time point of a station and those of its neighbours [9]. If a station has received a burst from its neighbour being located in its receive range, it can determine, whether this neighbour has the same reference time point or, how many periods (each 12.9μs) the time difference has. On this background the proposed decentral algorithm works as follows: Consider station i has received n packets from its different neighbours $j (j = 1, 2, ..., n)$ in the current frame. The synchronization point of station i at time t can be denoted as $SP_i(t)$, and those of neighbours are expressed as $SP_j(t)$. The synchronization deviation $\Delta T_i(t)$ in the view of station i can be averaged:

$$\Delta T_i(t) = \frac{\sum_{j=1}^{n} \Delta T_{ij}(t)}{n}.$$

where $\Delta T_{ij}(t)$ denotes the synchronization difference between station i and its neighbour j:

$$\Delta T_{ij}(t) = SP_i(t) - SP_j(t).$$

In the next frame the synchronization point of the station i is corrected to the new time position of:

$$SP_i(t+1) = SP_i(t) - \Delta T_i(t).$$

This process is repeated periodically in each frame for each stations.

Algorithm CSO

The second synchronization algorithm called CSO (Correction of synchronization according to Subjective Opinions), in which the correction of synchronization is determined by averaging received subjective opinions about the quality of the current synchronization point from the neighborhood and from the station itself.

Besides of slot identification SlotID each station i transmits in its data burst implicitly a subjective opinion Z and a priority of the current synchronization point of the station. Value Z represents the time distance in periods between its current synchronization point and its subjective reference time point, which is generated from the DCF77 receiver (see also the previous section). In conflict situation the synchronization point with the highest priority will be taken over.

The synchronization point of a cluster of stations should be corrected step by step, according to the subjective opinion of all neighbour stations, to the "optimal" one, so that even in a correction phase the time difference of neighbouring stations will be limited within the predefined tolerance range. If a station has more than N neighbours, it can gather enough information to decide whether the SP should be corrected or not. So it adds received subjective opinions together and compares it to a predefined threshold M. If the value M is exeeded, the current synchronization point is corrected exactly one period forward or backward. After receiving a burst from the neighbour having corrected its synchronization point, the station will take over this point, if the received priority is the highest, otherwise the correction of the synchronization point will be ignored. The detailed specification of this algorithm can be found in [9]

5 Performance Evaluation

Performance evaluation of the synchronization protocol ESDA is carried out with the consideration of its supported medium access protocol DCAP/DMAR [10] [4], so that some important performances as throughput and receive rate can be evaluated.

A simulative study was carried out to evaluate the performance of the protocol in a more realistic environment. The used simulator is a discrete time oriented tool, developed specially for the simulation of SR-MRN [11].

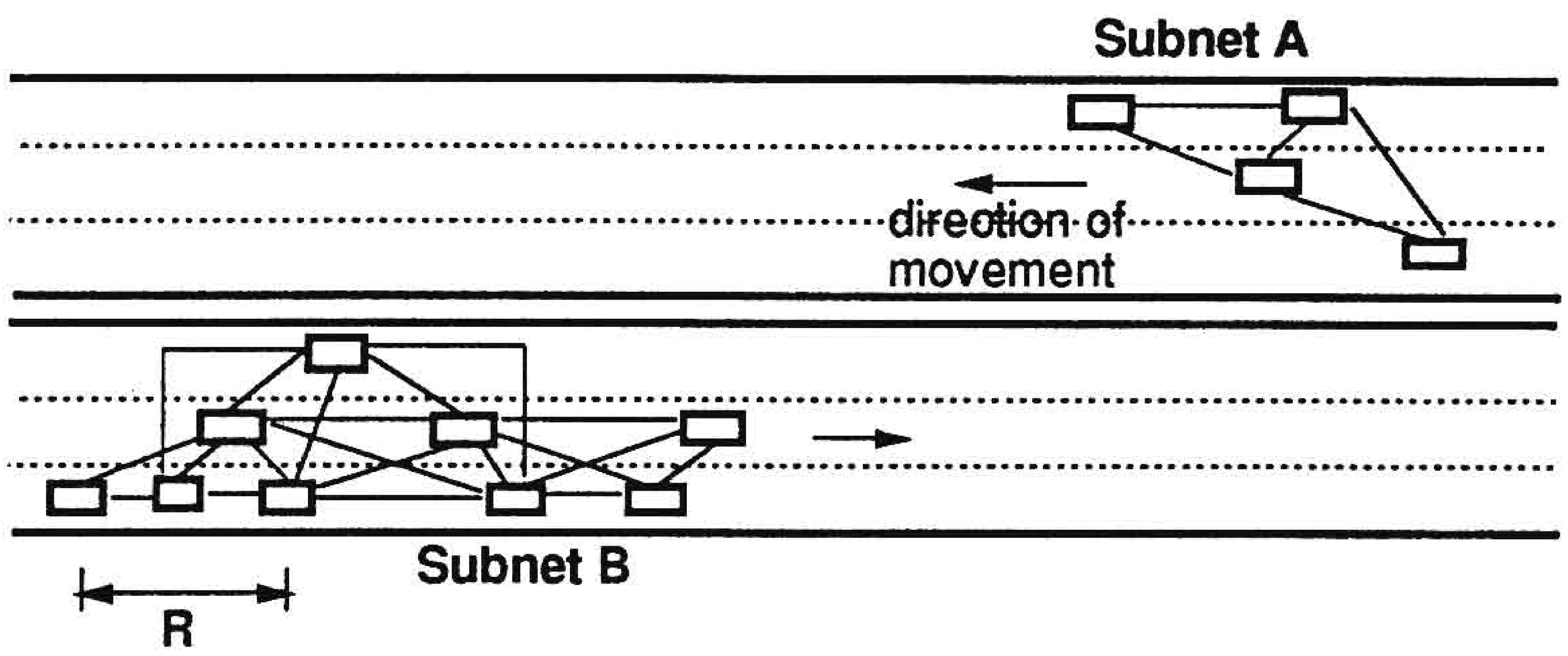

Figure 7: Simulation Scenario: Merging case of two clusters of stations

The simulated scenario (Fig. 7) describes a merging case of two independently synchronized clusters of mobile stations, which move in opposite directions. The connectivity within a cluster of stations is kept unchanged. Two clusters near each other and then merge to each other and finally separate from each other again into two clusters.

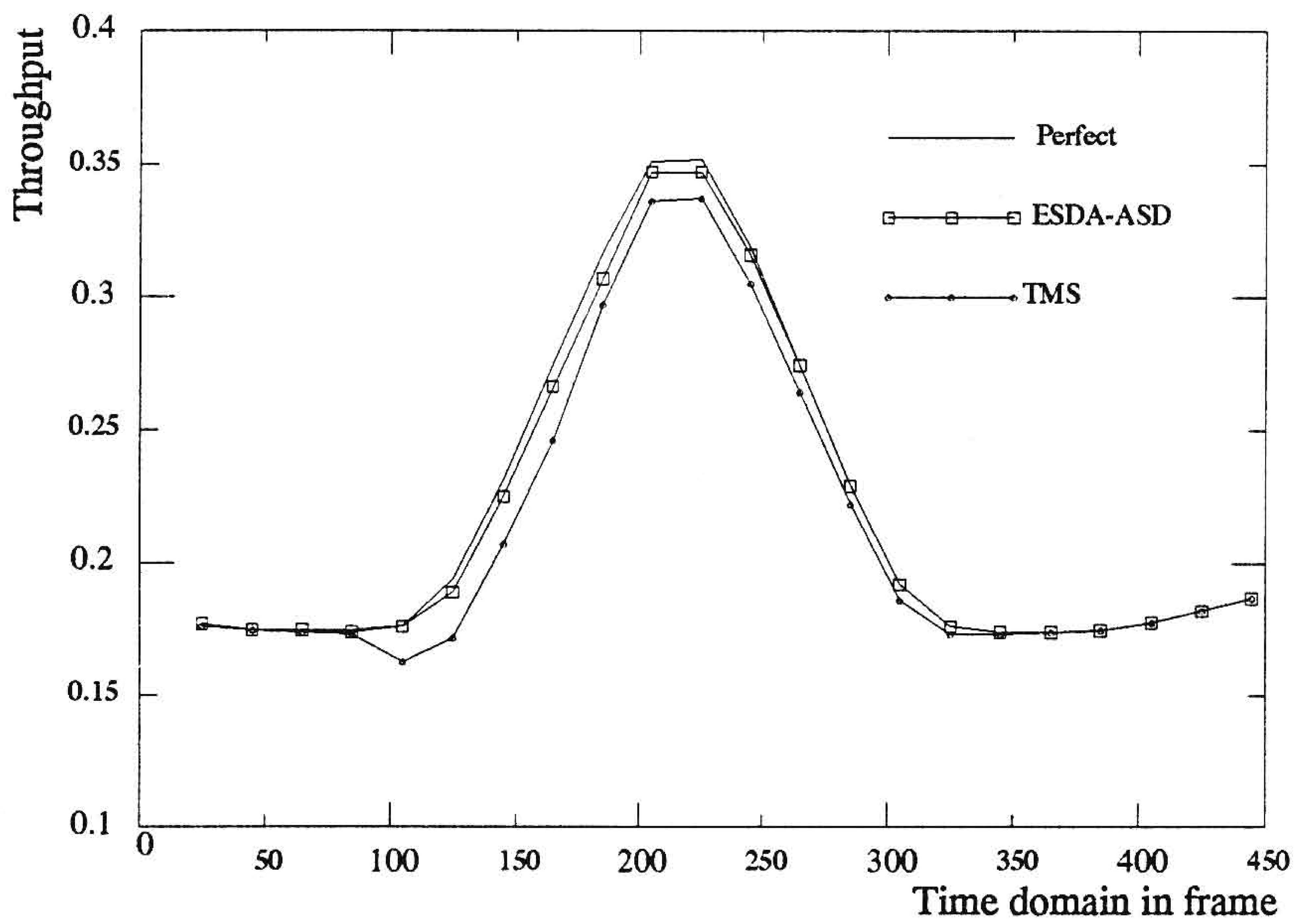

Figure 8: Comparison of throughput in time domain of the merging case

The simulation results of ASD algorithm and a totally decentralized synchronization algorithm TMS (Tansmit Majority Synchronization) [7] under the simulated scenario are shown in camparison with the results of a hypothetically perfect synchronism (Fig. 8 and Fig. 9).

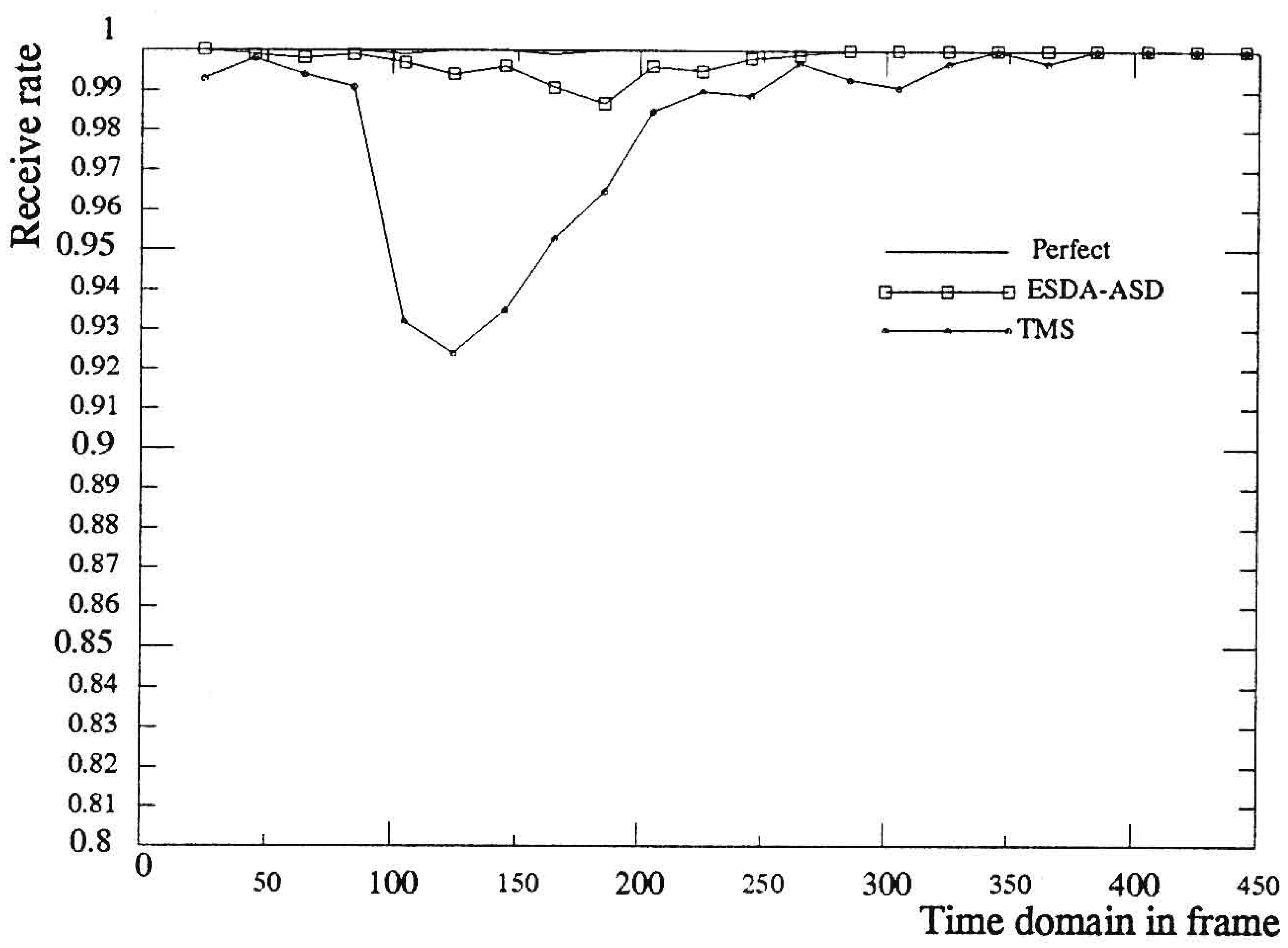

Figure 9: Comparison of receive rate in time domain of the mergin case

Because of randomly determined synchronization points at the initialization phase of the totally decentralized synchronization algorithm TMS, stations can be synchronized nearly perfectly within a cluster. But as soon as two or more independent clusters merge to each other the performance of the protocol drops down, since the clusters of stations cannot be synchronized in time. It is not difficult to see from the figures that the degradation of the performance is specifically dramatical at the beginning of the merging phase, where two clusters at the 50 th frame begin to interfere each other and at 100th frame begin to merge to each other. The performance of the ESDA-ASD algorithm is, in contrast to the TMS, near to the perfect one.

6 Conclusion

A local TDMA frame synchronization protocol called ESDA for short range mobile radio networks is proposed and evaluated in this paper. The radio clock signal DCF77 is used as external global time reference by each station, and a decentral operated synchronization algorithm adjusts the global time reference to accomplish the required accuracy. The experimental equipment for evaluating the accuracy of the time reference in mobile environment for the application is introduced. Experimental results shows that each mobile DCF77 receiver can conserve a definite zero crossing at the falling shoulder. Simulation results show, that the performance of ESDA is much better than that of the totally decentralized synchronization algorithm, and almost near to the perfect one.

The development of a superheterodyne receiver controlled with a micro processor is currently underway to improve the receiption characteristics of the low level signal, and we hope we can show the improved results in a few months.

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