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A High Precision TDMA Frame/Slot Synchronization Protocol based on a Radio Clock Signal — New Results

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Abstract

A local synchronization protocol for short range mobile radio networks (SR-MRN) is described, which is based on the time signal of a radio clock. This signal is used as a global time reference to establish local frame and slot synchronism of mobile stations communicating via a TDMA radio network.

Since a small transmission range below 1km is used, only local synchronism of mobile stations (vehicles) being in their respective interference range is necessary. Due to large number of slots per frame and high total transmission rate about 1Mbit/s estimated neccessary for the SR-MRN, the accuracy of synchronization must be up to some microseconds. As the reference signal transmitted from the radio clock cannot reach this accuracy on its own, a synchronization algorithm operating in each station is developed to achieve the required accuracy decentrally. The algorithm is based on the fact, that the receive range of communicating stations is about 1km, and potential synchronization points can be derived deterministically in time from the radio clock carrier.

The application of the radio clock DCF77 signal for high precision synchronization in a SR-MRN is defined. Experiment equipment aimed to receive the reference signal with high quality and low cost in mobile environment, and to evaluate the reliability and accuracy is introduced. A decentrally operating synchronization algorithms is described, performances of the medium access protocol DCAP/DMAR supported by the synchronization protocol compared to a hypothetical perfect synchronism is evaluated.

1 Introduction

As well known the short range mobile radio PROMETHEUS network (SR-MRN) is characterized by its ability to support continuous and real time data communication between vehicles and with beacons. Reliable transmission channels are required. Medium access control protocols [HeWa90][ZhHeWa91], 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 frame synchronization protocol has to be developed.

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

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transmission (about 1Mbit/s) and relative short slot duration (some hundred microseconds). Carrier frequencies at 6GHz and 60GHz are candidates for the SR-MRN and a transmission range of about 1km is specified by COPDRIVE. Only local synchronism covering mobile stations (vehicles) being in their respective interference range is necessary. Stations located sufficiently distant away need not be synchronized, because they cannot interfere each other. Since mobile stations using PROMETHEUS services are distributed all over Europe, an appropriate global synchronization signal distributed from a central transmitter appears advantages. The GPS sattelite system requires a costly receiver, but provides a high precision synchronization signal. A low cost alternative is to use the low precision signal of a radio clock and add some intelligence to the receivers to reach the desired precision.

Another possibility is to rely only on decentral operated synchronization algorithms. They are based on autonomously selected synchronization timing without any external reference signal, and are able to synchronize all stations having radio contact to each other (a net). Such methods, however, have a common and unavoidable disadvantage: In case of merging or crossing of two or more nets with different timing, poor performance like degradation of throughput and increasing delay is resulted.

In this paper we describe a high precision local frame and slot synchronization protocol based on a global time reference and a decentral operated algorithm in each station to achieve the required synchronization accuracy of several microseconds, and to avoid the above mensioned disadvantages. The time reference for seconds transmitted by the radio clock transmitter DCF77 is used for the synchronization. Because of the narrow band transmission of this signal, the reachable accuracy is up to 0.5ms. A decentralized synchronization algorithm, based on averaging of the synchronization timing of neighboured stations, is developed for the precision synchronization.

In the following sections we first introduce the application of DCF77 as a time reference for the high precision synchronization, experimental equipment to receive the reference signal with high quality and low cost in a mobile environment and to measure the accuracy of the generated synchronization signal. Then we describe the proposed synchronization algorithm. A realistic simulation model is described in section four, and evaluation results of the medium access protocol DCAP/DMAR supported by this synchronization protocol as well as by a hypothetical perfect synchronism are presented and compared in the fifth section.

2 Application of DCF77 and its Experimental Equipment

DCF77 is a radio clock transmitter situated in Mainflingen about 25km southeast from Frankfurt/Main. Because of the long wave characteristic of the 77kHz signal the transmission range of the space wave can reach a distance of about 2000km, which is related to the distance from Frankfurt/Main to Ankara, — it covers the range of whole Europe.

The radio clock transmits an amplitude modulated digital signal at a high stable ($10^{-12}/day$) carrier frequency of 77.5kHz. At the beginning of each second the carrier amplitude drops to about 25% with a duration of either 100ms or 200ms, whereby time is coded in minutes, hours, days and so on (see Fig.1) [Hilb87].

We are interested in the falling shoulder of the carrier signal at the beginning of each second (shown in Fig.2), which is used as global synchronization reference. The duration of the

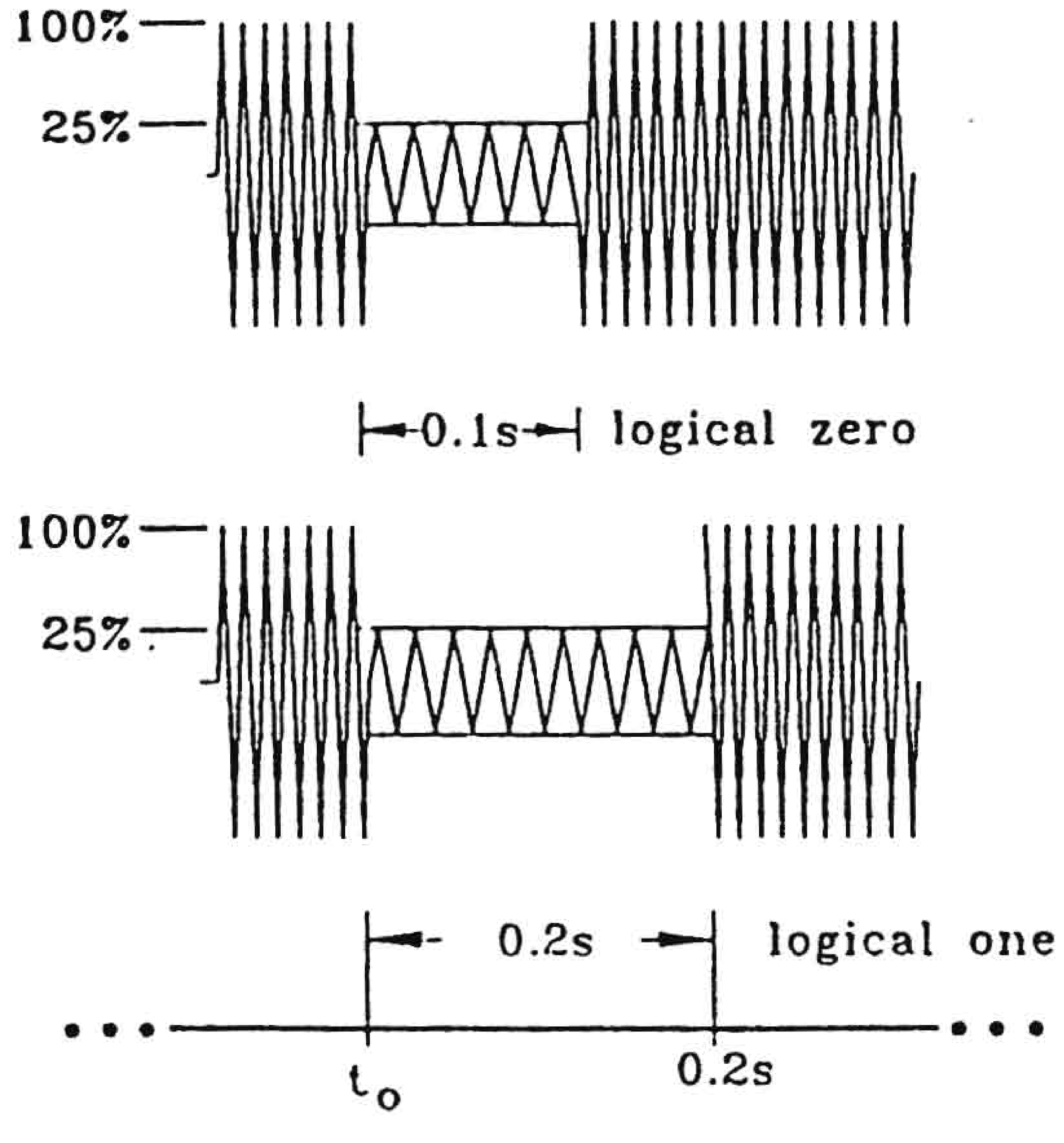


Fig.1 Amplitude modulated signal

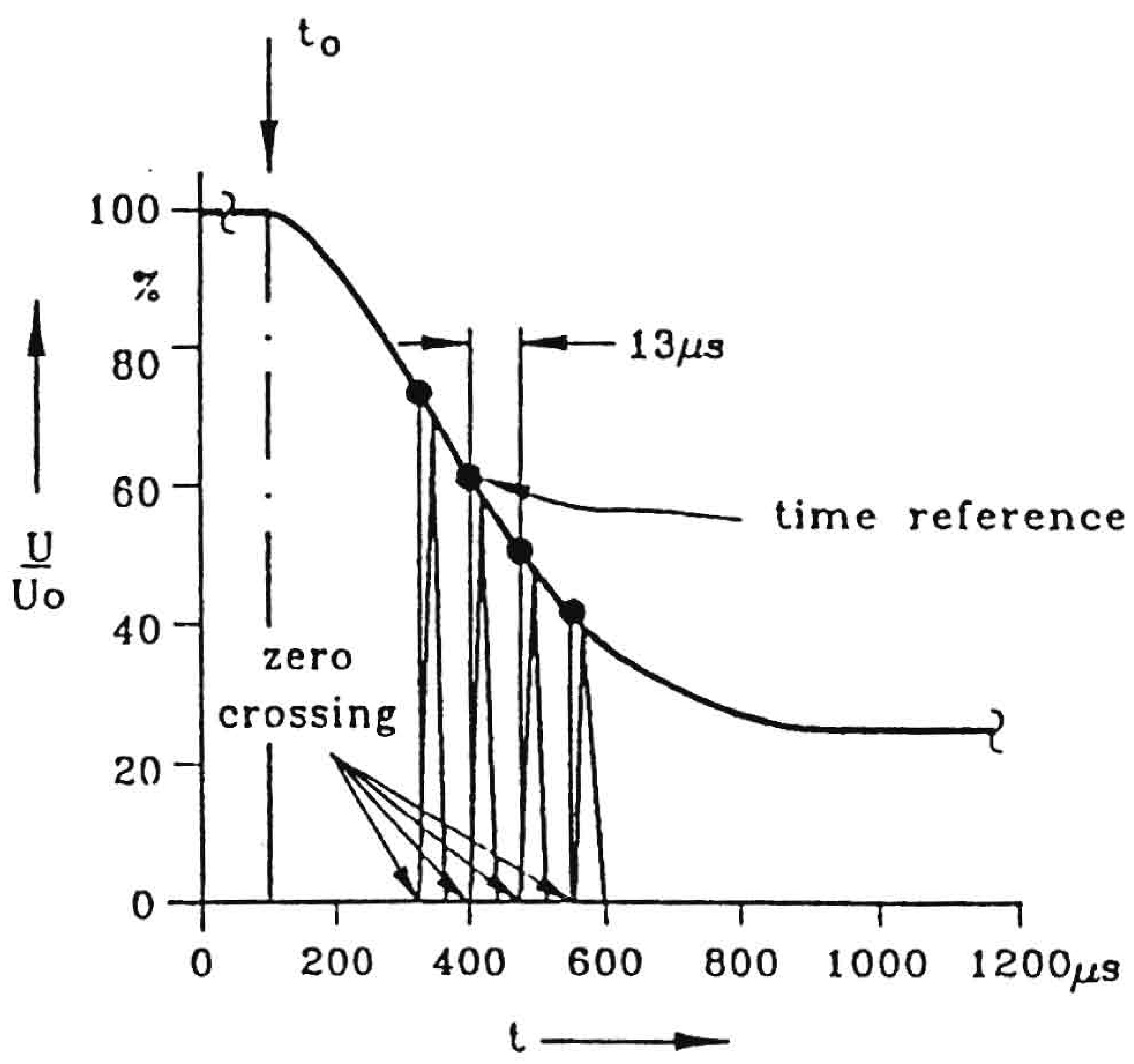


Fig.2 The shoulder of the radio clock signal

shoulder is about 0.5 milisecond. The shoulder can be divided into about 38 points marking the times of positive zero crossings of the carrier signal, having a period duration of 12.9 μs. Because of the high stability of the carrier frequency these zero crossings can be used for synchronization of stations in our proposed synchronization algorithm, in which each station independent selects an "optimal" point near the middle of the falling shoulder, when its receiver is switched on. Only these time discrete points are permitted to be selected and to be used as a synchronization point.

Reports on the stationary receive behaviour of the DCF77 from different distances with various receive conditions can be found in [Hilb87],[Hetz87] and [Bade87]. In order to receive the reference signal with high quality and low cost in a mobile environment, and to evaluate the statistic behaviour of the synchronization points selected independently by stations, an experimental equipment is defined.

This equipment consists of two seperate parts, namely receiver part and an absolute timing reference used to measure the accuracy of the synchronization (see Fig.3). The DCF77 radio clock signal will be received in the first part. For an zero crossing near the middle of the falling shoulder, a second impulse will be generated and transmitted out from the receiver part as the subjective selected synchronization point for the station equipped with this DCF77 receiver. Considering overlapping behaviour of space and earth wave in different places, and mobility of receiver equipped in a mobile station, the receiver should be more compact and stabler then in stationary case.

The trigge point (working point of the synchronism) is selected at about 60% to 80% of carrier amplitude on the falling shoulder, because on one side the steepniss of the flank at above range is the largest, and on another side the change of the falling shoulder at a higher trigge point is less noticeable as a lower one [Hetz87].

If a vehicle is driven into a long tunnel or in some other extremely situations, the signal will drop or be losed to the receiver. In this case the receiver generates substitute second impulses unitl the signal of second beginning can be received again.

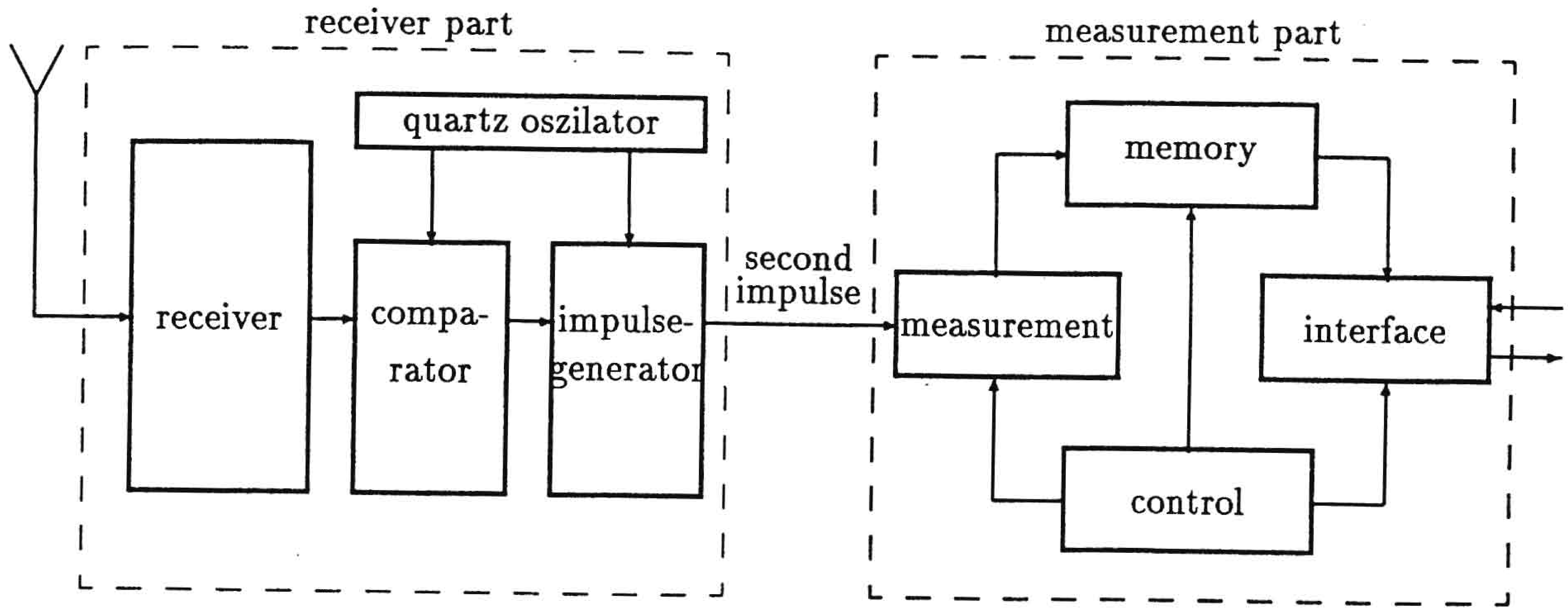


Fig.3 Experiment equipment

The measurement part has the functions measuring the accuracy of the second impulse transmitted from the receiver part, and store the measured data to the memory for further statistic analysis. As the measurement part has to be operated in the mobile environment as well, it should have the same requirements as the receiver part such as compact, stable and transportable. Besidse it should operate continously and undisturbed by power switch off and switch on during the measurement in mobile environment.

3 The Synchronization Algorithm

As mentioned before the reachable accuracy only through DCF77 signal is about 0.5 miliseconds. We assume that each station is equipped with a DCF77 reference signal receiver, and is able to select an "optimal" point on the signal shoulder as its synchronization point. The points selected independently by each stations are assumed to be statistically distributed according to normal distribution.

The following goals have to be achieved by this algorithm:

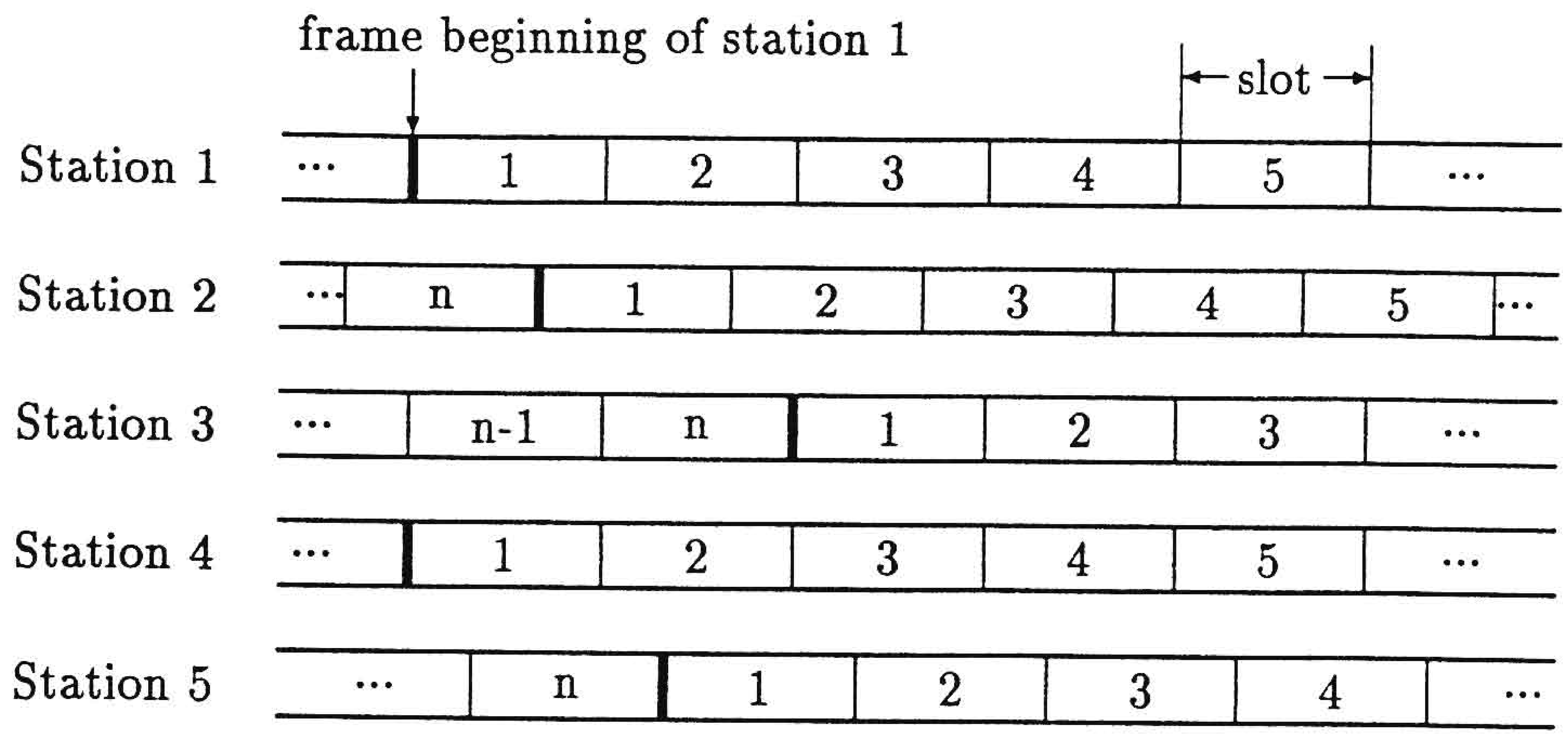
- Local synchronization (frame and slot synchronization of stations in a net) should be reached rapidly to support reliable channel switched communication between mobile stations being in their respective receive range.
- If two or more nets merge with each other, the synchronization timing deviation between different nets should be within a tolerable time range, so that the existant communication channels of different nets can be used without loss of quality caused by interruption and interference.

Once a station has selected its synchronization point or has corrected it according to the averaged opinion of neighbouring stations to some other point (see follow), it will conserve it whereever it moves to. Ihis is possible because a station can receive the falling shoulder once a second.

The slot number in the frame is transmitted in each slot, so that the frame beginning is also known to the receiver, if the contents of a slot (packet) has been received.

To take signal propagation delay of the radio clock as well as from neighboured mobile stations into account, a guard gap (e.g with a duration of 6.6 μs) must be included in each slot. The duration of the guard gap is related to the propagation delay of 1km forward and backward.

If a station has received a packet from its neighbour being located in its receive range, it can determine, whether this neighbour has selected the same synchronization point or, how many periodes (each 12.9μs) the difference amounts. In Fig.4, for example, station 1 is frame synchronized with station 4 but not with station 2, 3 and 5.



Station 1 and 4 are frame synchronized, Station 1,3 and 4 are slot synchronized.
Fig.4 Determination of synchronization

On this background the proposed decentral algorithm works as follows: When stations with individually selected synchronization points approach each other, each can observe the synchronization timing of its frame periodic of transmitting neighbours using nonoverlapping slots. A station measures the individual time difference to any neighbour, takes the average and uses the result to correct its slot beginning in the next frame. This process is repeated once per frame.

This algorithm can be mathematically described: Consider station i has received n packets from 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 error $\Delta T_i(t)$ between station i and its neighbours averaged can be expressed as:

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

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 position of:

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

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

As all stations have the same global time reference and each net of stations is synchronized by this algorithm to an average point in time from all individually selected points, the synchronization error of independent nets can thus be limited to a tolerable time range. The simulation results show, that there is no performance degradation by nets merging.

4 Realistic Simulation Model

In this section the funtionality and construction of the simulator as well as the realization of the medium access control protocol DCAP/DMAR, supported by a realistic physical channel model for the GHz range, is described.

4.1 Construction of the Simulator

The simulator is a discrete event oriented tools, developed specially for simulation of SR-MRN. It is implemented under the VAX/VMS operating system in MODULA-2. It consists of three basic elements of road environment, mobile and stationary vehicles (stations) and radio communication protocols.

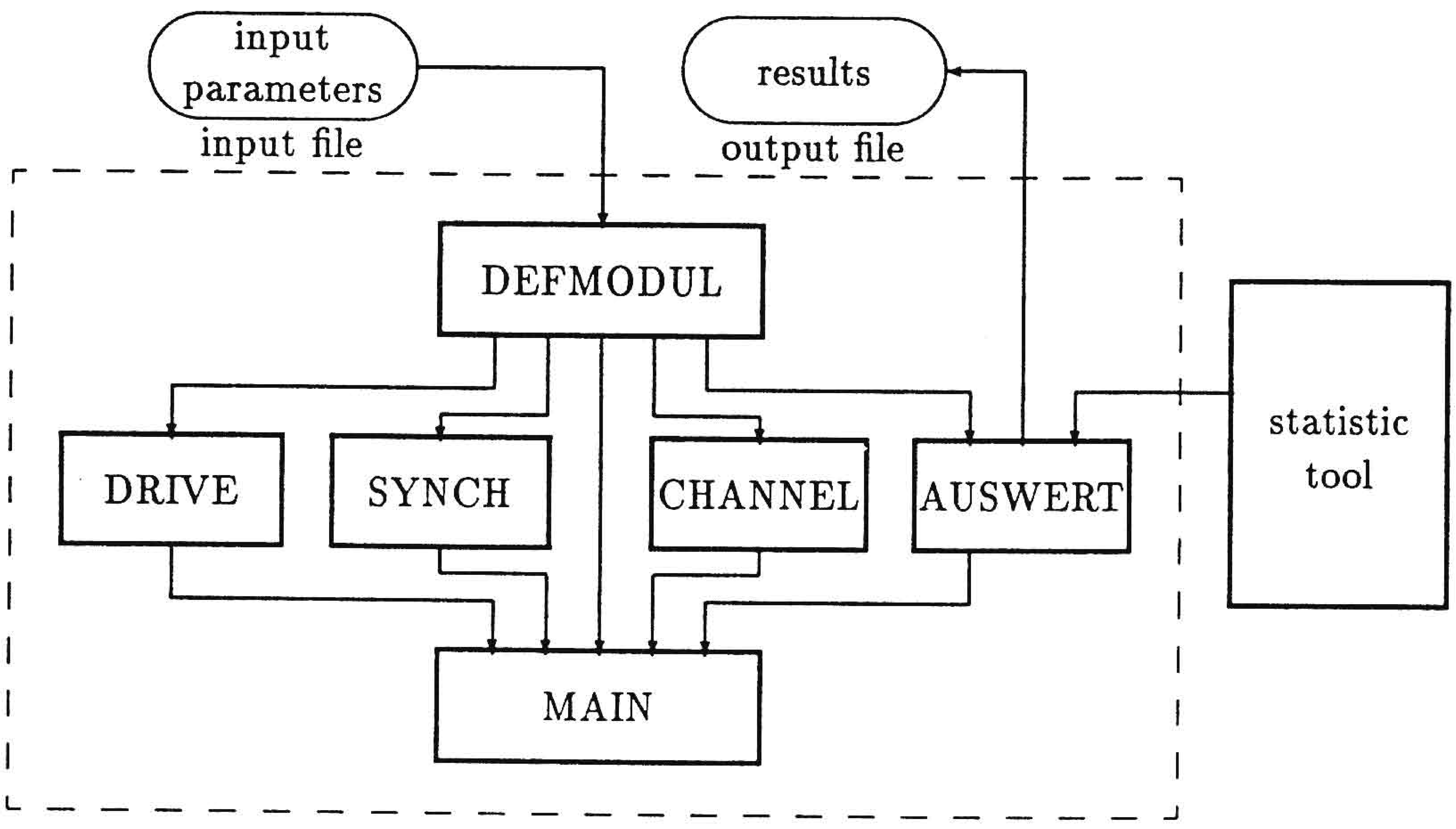


Fig.5 Construction of the simulator

The construction of the simulator is shown in Fig.4. The simulator comprises six independent modules, whose connections are facilitated through the import and export of parameters and procedures of the modules.

The module DEFMODULE defines the configuration of road environment such as roads, lanes, crossings and roadside infrastructures, and determines current construction of station cluster(s) (forming a net) as well as the considered scenario by reading in the input parameters. Basic data structures of stations and common procedures for all other modules are defined in this module.

The module DRIVE simulates the station's mobility behaviours like velocity, acceleration, moving directions etc.

The logical channels and behaviour of the medium access protocol DCAP/DMAR with channel switched access technique, as well as a realistic physical channel model in the GHz frequency range for supporting real data exchange are implemented in the module CHANNEL. The realization of DCAP/DMAR is introduced in detail in the next subsection.

The developed synchronization protocol is simulated in the module SYNCH.

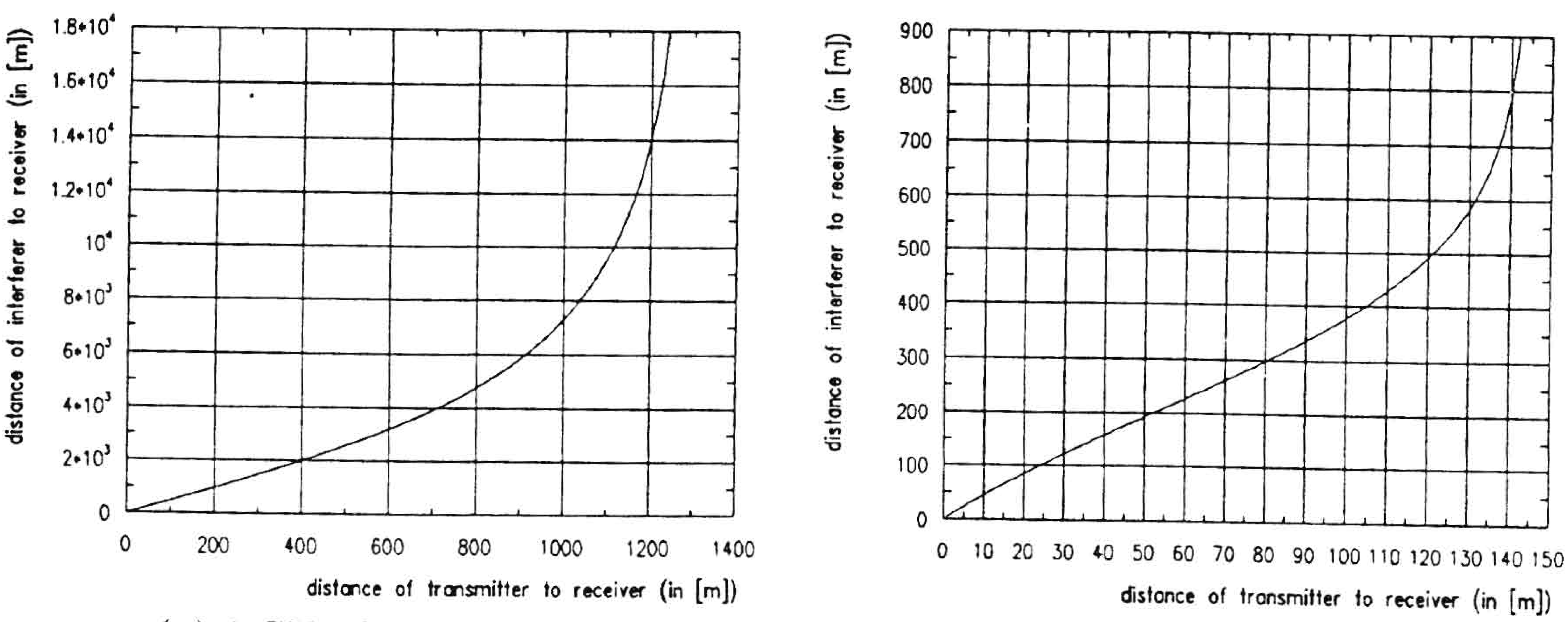
The evaluated data is analysed in module AUSWERT by means of statistic tools to get the performance of the simulated protocols in the mobile environment. Simulation results are written out to the output file.

The module MAIN obviously is the main module, which controls the execution of the simulation and contributes functions and procedures defined in other modules to simulate the system.

By change of parameters in the input file, different variation of the system, such as road envirenments, various clusters of stations and different protocol parameters can be simulated.

4.2 Implementation of Medium Access Protocol

A realistic physical channel model of the GHz frequency range described in [BSL89] is implemented in the module CHANNEL With this channel model for 6 and 60GHz, antenna characteristics and influences of wether conditions on channel characteristics can be simulated. The behaviour of transmission range and interference range by 6GHz and 60GHz is shown in Fig.6. If a signal is too week to be demodulated and decoded correctly at a receiver, it still can be strong enough to interfere and even disturb another transmission.



(a) 6 GHz Channel, 25mW (b)60 GHz Channel, 50mW

Fig.6 Transmission and interference range

The decentral medium access protocol DCAP/DMAR, which is supported by the described synchronization protocol is shortly reviewed in the following. A detailed description can be found in [HeWa89] and [HeWa90].

The protocol is based on a slotted TDMA frame, and supports real time oriented continous data exchange between neighbouring stations. In the SR-MRN hidden stations arise from the fact, that the stations typically are only partly connected. To overcome the problem, every station keeps book of the status of all N channels in a frame using one bit per channel. The respective N bits are grouped in a vector called bitmap, which is transmitted piggy-backed as part of each used slot. Evaluation of all bitmaps received from neighbored stations during a frame, together with the channel status observed by station itself, leads to a complete knowledge about all occupied channels in the one-hop plus detection range around a station. Used slots are defined to be implicitly reserved in the next frame according to the well-known R-ALOHA protocol [Lam80]. If a channel is indicated to suffer from increasing co-channel interference, the respective transmitter is forced to perform a handover to another channel currently known as locally unused from its gathered bitmaps. If a new channel has to be established, the status about channels known from own observations and received bitmaps is used to establish a new channel.

DMAR (decentral multiple access protocol with reservation) is a further developed version of DCAP. It relinguishes to transmit the bitmap in each data slot. Instead of that, the channel quality information is only transmitted occasionally, whenever a channel handover is requested.

In our implementation of medium access control protocol, we do not distinguish between DCAP and DMAR (call it DCAP/DMAR) by assuming that:

- bitmap information of each packet is correctly received by neighbour stations in time.
- if a channel is occupied by a transmitter, or interfered, it is marked "1", otherwise "0".
- if a packet is successfully transmitted, the related throughput is counted as 1, regardless of part of data being used to carray the bitmap.

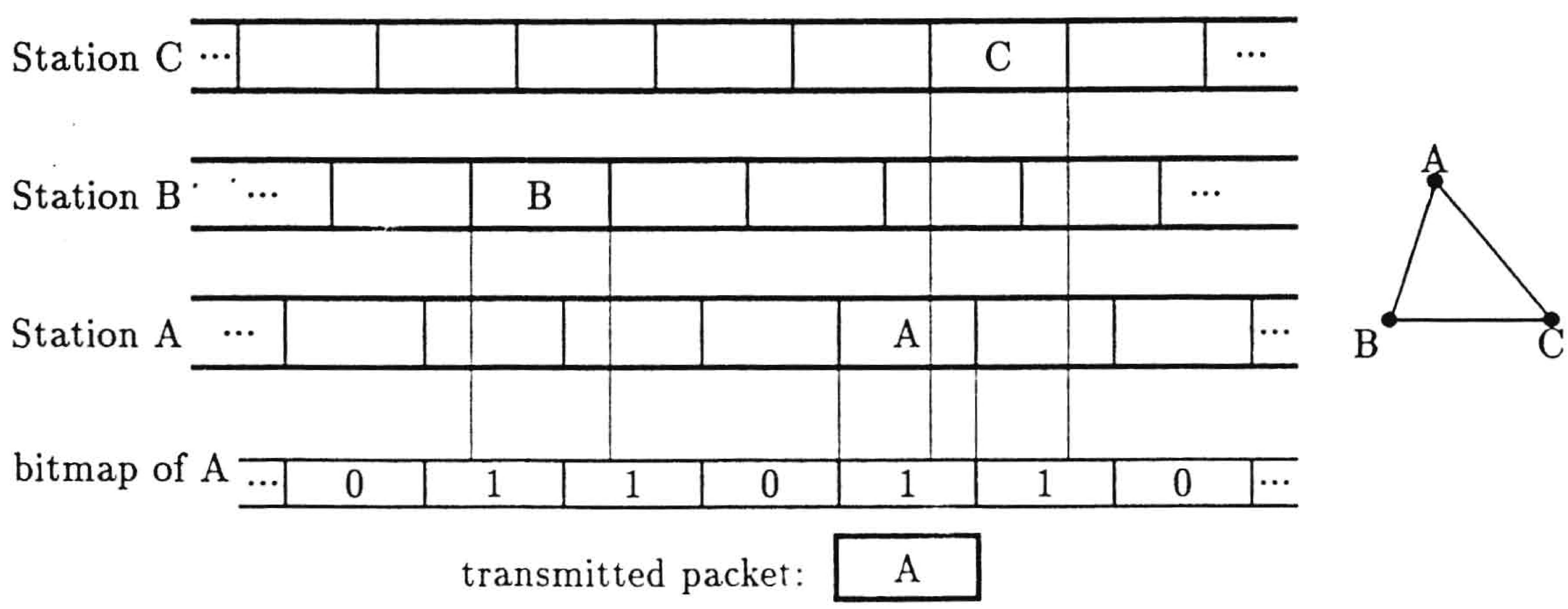


Fig.7 Determination of observed onehop bitmap

The DCAP/DMAR need a synchronous TDMA structure on the channel. In order to evaluate the performance behaviour of the protocols supported by our synchronization algorithm, the following modifications and externsions were made for the not synchronized case:

- A not synchronized transmission results in two bits set to "1" in the bitmap observed by any neighbour. Fig.7. sketches the way how a station (station A) determines its observed onehop bitmap.

- Each station uses exactly one slot in each frame and,

- If a station has to handover its transmission channel and find no any free one from its gathered channel occupation information, it will suspends the handover and transmits on the old channel until free channel is found.

5 Simulation Results

It must be mentioned here, that our main interest is not to evaluate efficency of the medium access protocols, but the performance of the described external decentral high precision synchronization protocol (EDS), and its suitability to support channel switched medium access control protocols such as DCAP/DMAR. Their performance behaviour, synchronized by EDS in comparation using a hypothetical perfect synchronization were simulated.

The following parameters are choosen for the simulation:

- 60 GHz transmission channel

- 50 mW transmission power by each station

- 1Mbit/s data transmission rate and 0.1s frame duration

- number of channels 40

- tolerable synchronization error: 1 period of DCF77 carrier (12.9μsec)

No moving direction oriented channel allocation [HeWa89] is used in the simulation. Because of partly meshed stations in the SR-MRN and broadcast (point to multipoint) oriented communications, some definitions have to be introduced first, which help to understand the simulation results.

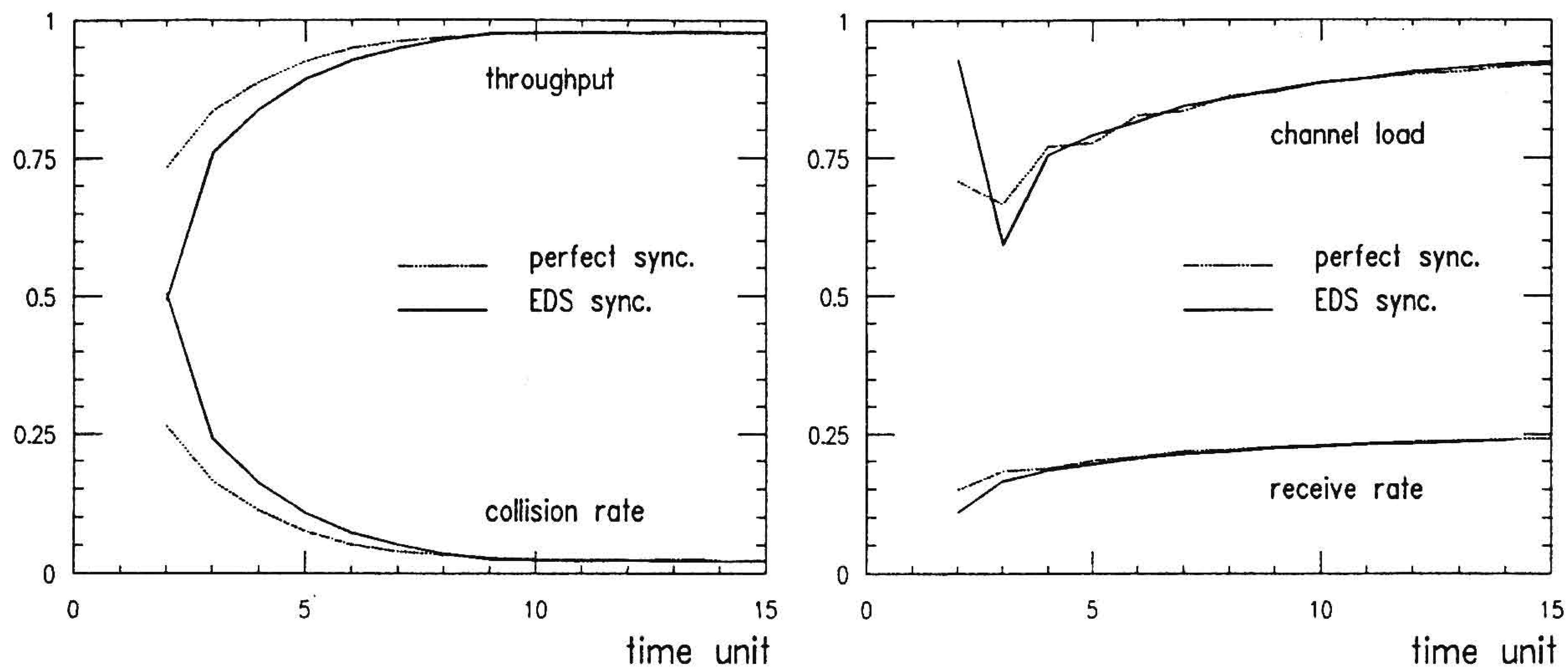
- **Throughput** denotes the ratio of number of successfully received packets to number of packets, which should successfully be received without collision.

- **Receive rate** is defined as the ratio of number of successfully received packets in a frame to number of channels (slots) in a frame.

- **Channel load** represents the ratio of number of occupied plus interfered channels in a frame to number of channels (slots) in a frame.

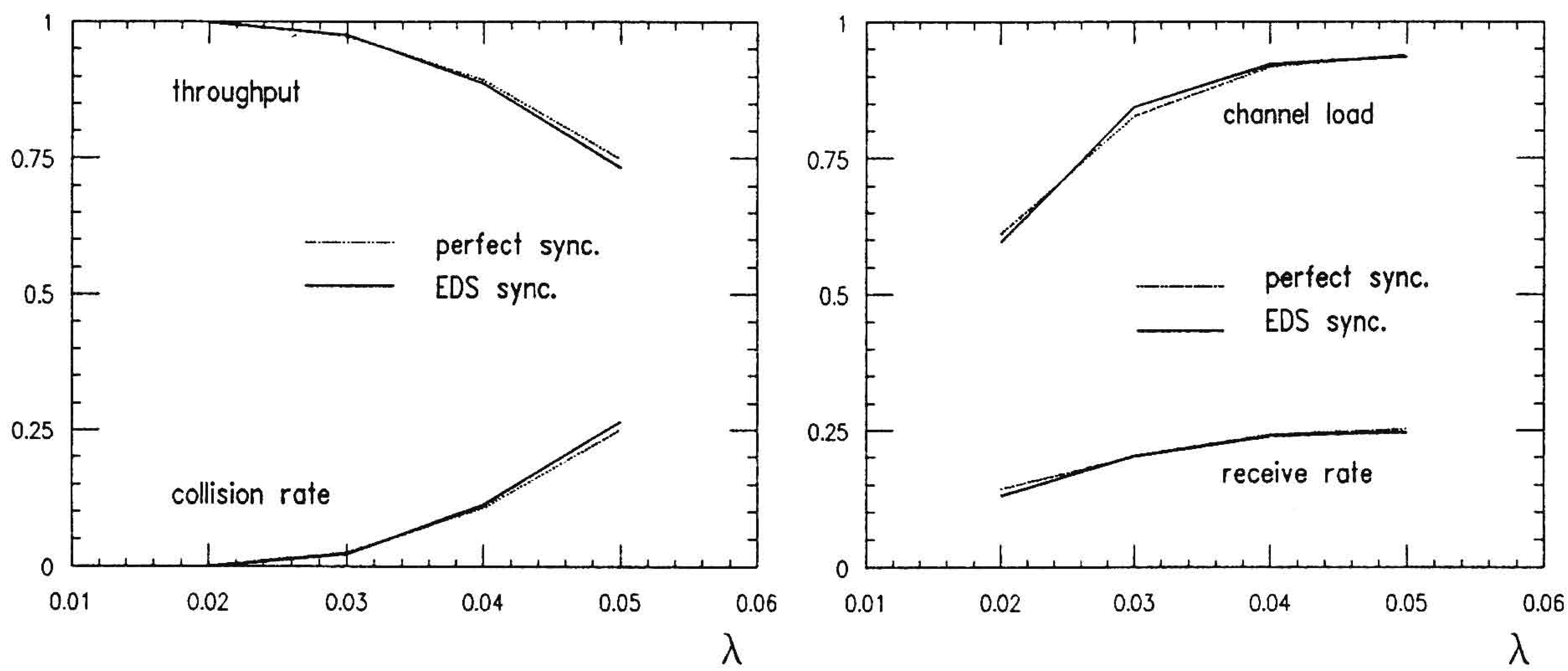
- **Collision rate** is defined as the ratio of number of collided packets to number of packets, which should be successfully received.

Two scenarios were simulated to evaluate the performance behaviour of the synchronization algorithm in different situations. In the first case cluster of one hundred stations are randomly distributed on the road. To observe the influence of the synchronization process on the medium access protocol, we have simulated the initialization phase of the synchronization of DCAP/DMAR. Each station selects subjectively an optimal synchronization time point. Because no bitmap information is available at the beginning, stations select channels



(a) Throughput and collision rate (b) Channel load and receive rate

Fig.8 Initialization Scenario: λ=0.03 stations/meter



(a) Throughput and collision rate (b) Channel load and receive rate

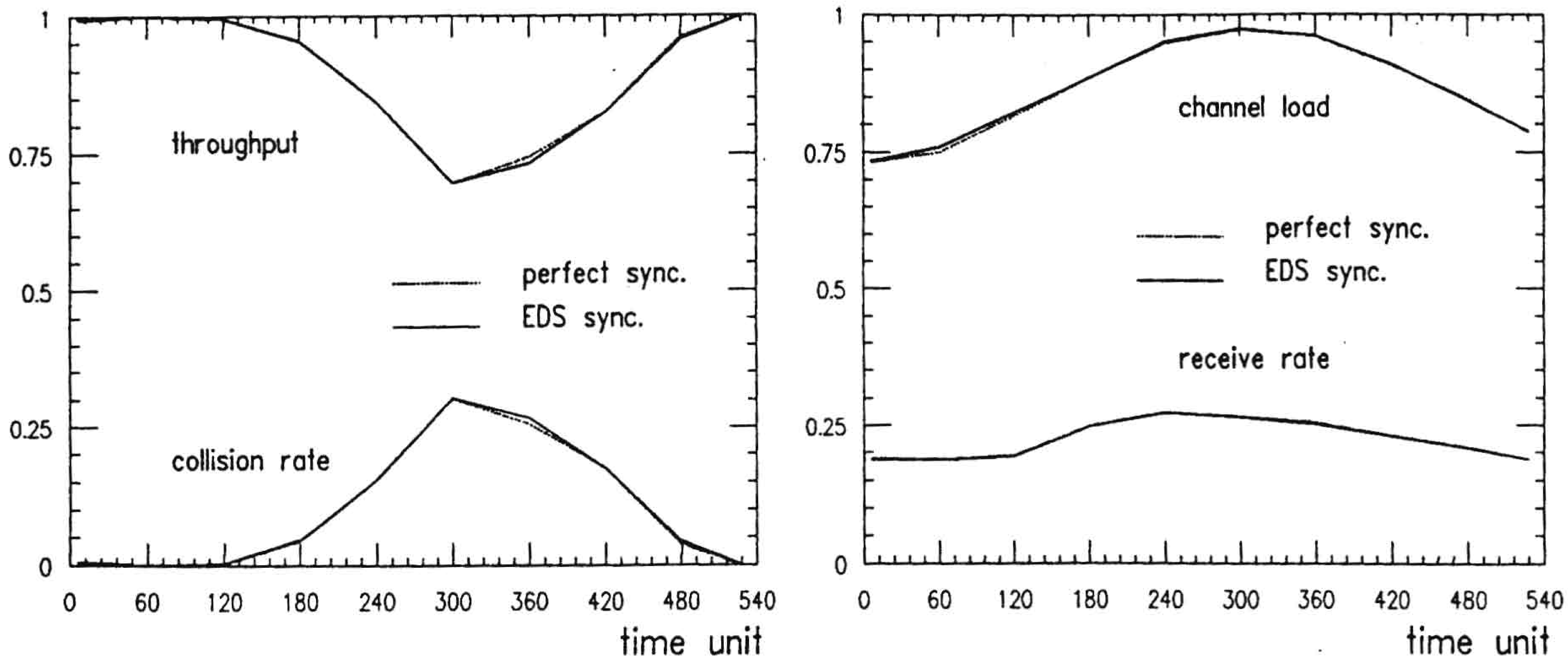
Fig.9 Singel net scenario in stable state

randomly to transmit their packet. Then, both protocols EDS and DCAP/DMAR are executed step by step in each station of the cluster, until a stable state is reached.

Fig.8 describes the performance of this process with the station density $\lambda = 0.03 stations/m$. The time unit counts in frames. A performance degradation under EDS compared to the hypothetical one can be observed at the beginning. The difference disappeares after 6-7 time units, where the stable state of the protocol is reached.

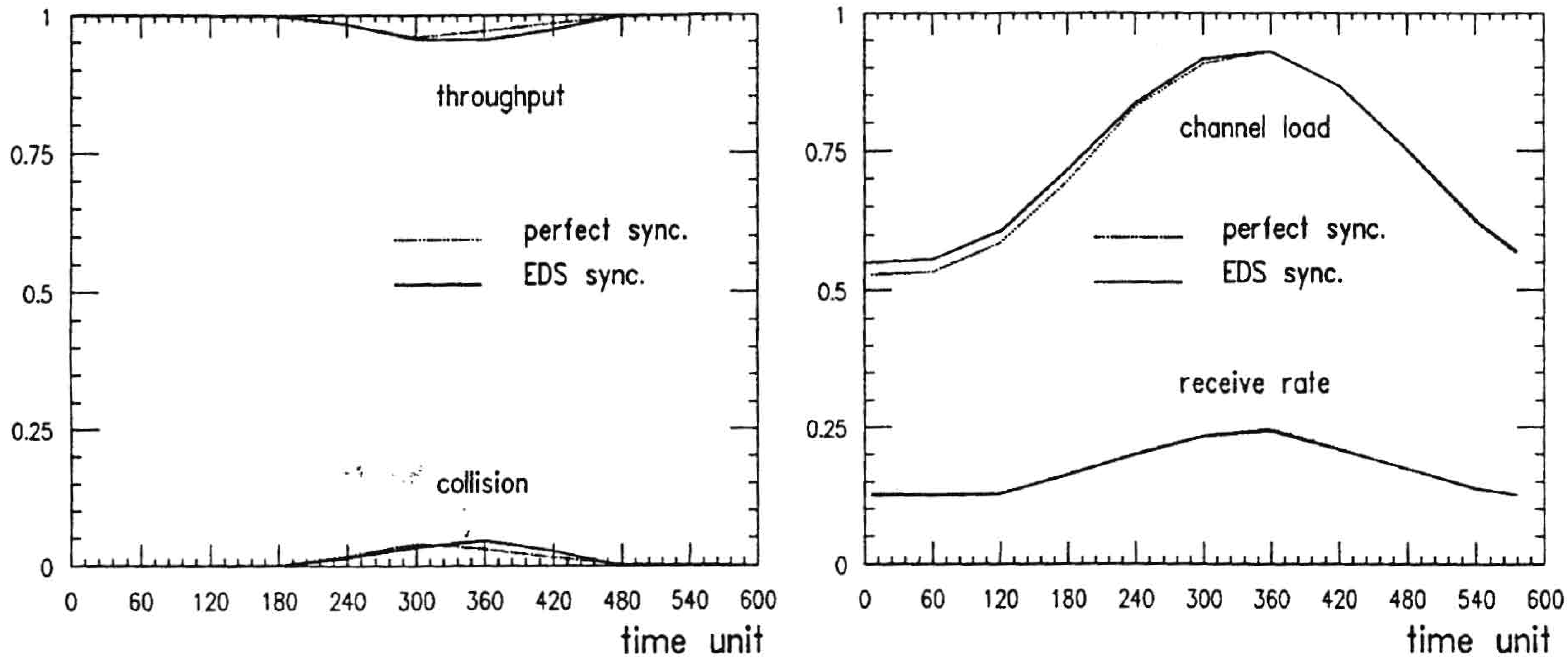
Fig.9. shows the performance in stable state with a parameter density λ of station. The performance of EDS and the perfect synchronisms is almost the same.

In another scenario the merging process of two independent nets is simulated. At the beginning each net is synchronized and operated on their own, independently, and both nets cannot interfere each other. Because of different moving speed and even different moving



(a) Throughput and collision rate (b) Channel load and receive rate

Fig.10 Merging scenario: heavy traffic



(a) Throughput and collision rate (b) Channel load and receive rate

Fig.11 Merging scenario: low traffic

directions they approach each other. Fig.10 and 11 show the performance of the simulated protocols in this process, with high and low communication traffic.

A comparation of the performance of the DCAP/DMAR protocol shows that EDS and perfect synchronization perform nearly the same. Because the synchronization error of two different nets during merging is in the tolerable range of 12.9μs (see section 3).

The throughput degradation in Fig. 10(a) and 11(a) results from the insufficient channel capacity available for the large number of clustered stations of two merged nets. If a handover has to be performed by a station, no free channel probably can be found (in the case of a channel load near 100%).

6 Conclusions

A decentralized local TDMA frame synchronization protocol for short range mobile radio networks is proposed and evaluated in this paper, in which the radio clock signal DCF77 is used as global time reference by each station. The experimental equipment for evaluating the accuracy of the time reference in mobile environment for the application is introduced. A decentral operated synchronization algorithm, based on averaging the synchronization timing of neighbored stations is described in detail.

The performance of the medium access protocol DCAP/DMAR, supported by this synchronization algorithm EDS is simulated in a realistic environment. Simulation results show that the EDS synchronization has a excellent performance within a cluster of stations, as well as during the merging process of two or more independent nets.

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