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Technology and Management of Traffic
Preliminary Communication
U. D. C. 656.25:621.396.2:62-182.3
Accepted: May 17, 1999
Approved: Oct. 5, 1999

SOME SIGNAL PROPAGATION AND TRAFFIC HANDOVER ASPECTS OF A MOBILE RADIO NETWORK FOR HIGH-SPEED RAILWAYS

ABSTRACT

Taking advantage of GSM's elaborated mobility management and its international roaming capability, the International Union of European Railroad Operators (UIC) has decided to build a supra-national rail radio network based on enhanced GSM technology.

In this paper, some implementation aspects specific to railroad radio environment resulting from the effects of vehicle speed - in particular Doppler shift - are discussed, and an "off-line" algorithm for the traffic handover is proposed, which offers better radio link reliability and less critical timing constraints than conventional handover schemes. More reliable handover is of vital significance in the case of high-speed trains since the radio link is supposed to carry the automatic control signals (ATC), too.

KEY WORDS

GSM, rail radio network, traffic handover, high speed trains

1. INTRODUCTION

Several European countries have begun to build railway lines with passenger trains operating at speeds around 300 km/h, so that such links may soon play a major role in European mid-range travelling. These comfortable high-speed trains travelling between European metropoles in a few hours only, may soon become the favourite transport means for a mid-range European traveller. The GSM' mobile radio has gained broad acceptance in Europe and many other countries all over the world. In 1993, the International Union of European Railroad Operators (UIC) decided to build a supra-national rail radio network based on GSM technology, which needed to be enhanced by additional features such as e.g. Group and Broadcast Calls, and Priority Setup Service.

Considering signal propagation aspects, direct radio coverage from outdoor cells is not practical due to numerous obstacles such as tunnels and artificial cuttings, while a repeater system mounted on the train would likely need to be of very high dynamic range. What additionally does not encourage the use of the existing public GSM networks for either railroad internal or passenger communication is the need for high reliability of the link, as it should also carry automatic train control (ATC) signals, which are vital at these speeds. In the following, we will discuss some relevant aspects of the network implementation and planning, as resulting from the effects of high speed.

1.1 Radio Aspects of Network Implementation

Decisive part for a mobile radio system is the radio transmission across the air interface. A mobile radio channel is subject to distortions of amplitude, frequency and phase. Amplitude distortions are due to fading effects, caused by landscape or man-made structures as well as multipath propagation, while distortions of phase are due to time dispersion caused by echoes from remote objects. Specifically, time-division-multiplex (TDMA) systems are very susceptible to time dispersion, so that sophisticated equalising methods have been developed to combat its negative effects. Additional systematic distortion of phase and frequency is caused by Doppler shift of the carrier frequency due to moving of the mobile. In quasi-static systems (e.g. DECT), this is often neglected, while GSM is designed for speeds up to 250 km/h. Applications for use in modern high-speed trains are expected to cope with even higher vehicle speeds (up to 500 km/h), where Doppler shift frequency distortions introduce additional phase distortions, which, in turn, strongly impact the achievable bit-error-rate (BER), and so the performance and reliability of the system.

1.2.1 Specific Railroad Radio Propagation Environment

The most common scenarios for the mobile radio considerations are mainly urban areas characterised by dense buildings, narrow street canyons and heavy multipath propagation. The corresponding properties of the mobile radio channel have been reviewed in [7]. Here we will deal with radio channel features specific for the railroad environment, where the operational environment is rather different. When trains go fast, flat open and mainly rural countryside prevails. In or near railway stations the environment can be modelled as of the suburban type [7]. Here the direct signal path is mostly available together with the multiple reflections and, consequently, the statistical distribution of the received signal envelope can be modelled by the Rician probability density function (pdf):

$$p(r)=\frac{r}{\sigma^2}e^{-(r^2+a^2)/2\sigma^2}I_0\left(\frac{ra}{\sigma^2}\right) \qquad (1)$$

with:

$$r=\frac{R\sqrt{2}}{E_0} \text{ and } a=\frac{A\sqrt{2}}{E_0}$$

where:

R – is the field strength of the reflected waves,

A – is the field strength of the direct path,

E_0 – is the average field strength of the fading signal and

$I_0(...)$ – is the modified Bessel function of zero order.

The Rician parameter $K=a/r$ is used to classify the channel. It is defined as the ratio of power of the direct path to the power of the sum of reflected paths. Its value of zero corresponds to the Rayleighian pdf while high values determine the Gaussian one [6].

Although GSM is designed for speeds only up to 250 km/h, operation at higher speeds seems feasible due to the favourable propagation conditions offered by typical railroad environment in the 900 MHz band which have been extensively investigated [1], [2], [3], [4]. Test transmitters were installed along the line, measurements were recorded onboard a special measurement train and obtained results evaluated. The main propagation characteristics for typical open rural area were found to be [5]:

- low delay spread and multipath propagation
- dominant direct path (Rician channel)
- typical value of the Rician parameter
- increase of the Rician parameter due to low antenna heights and small cells
- only minor influence of antenna patterns on results.

For a typical new-built high-speed train lines in various environmental conditions, the Rician parameter was found to be 8,13 dB. The necessary window width of the equaliser is less than 6 us (for the carrier-to-interference ratio of C/I=9 dB [4].).

1.2 Service Aspects of Network Implementation

In addition to the standard services defined in GSM standard by ETSI, such as speech, data, short messages (point-to-point and broadcast), some supplementary services are defined, too, such as: Call Forwarding, Call Barring, Calling Line Identification, Advice of Charge and Closed User Groups. The list of supplement services is constantly increasing as a means to attract subscribers. The UIC has decided to incorporate some functionality of *trunked* radio systems into GSM, such as:

- point-to-point connections (controller-to-driver link, automatic train control (ATC), remote control,
- group and broadcast calls (shunting radio, trackside maintenance, emergency calls, local communications at trains and depots, communication within the train),
- other (wide-area communication, passenger services, priority and pre-emption of calls, fast call setup).

2. EFFECTS OF MOBILE'S SPEED

It is of primary interest here to investigate how the GSM base and mobile stations cope with Doppler shift, particularly in most critical situations such as close passing by base stations and oncoming trains.

2.1 Demodulation at High Speed of a Mobile

GSM uses Gaussian Minimum Shift Keying (GMSK) modulation [7], which features constant signal envelope and so allows the use of power-efficient class-C amplifiers, while being resistant against amplitude distortions. The received signal is sampled at $\frac{1}{4}$ of the bit rate and a bit sample corresponds to a rotation of 90 degrees in the complex I-Q plane. If correctly synchronised and sampled, all samples will lie on 4 points in the complex plane (Fig. 2a). When a frequency offset (e.g. due to Doppler shift) is applied, the sample points will move from their expected positions clockwise or anti-clockwise, depending on the sign of the offset (Fig. 1a,b) and the speeds.

In practice, the samples will lie in "clouds" around the dots shown in Fig.1, due to superimposed noise and other channel distortions. Within the period of a timeslot, a sample should not move out of its nominal position for more than $\frac{\pi}{4}$ in either direction in order to

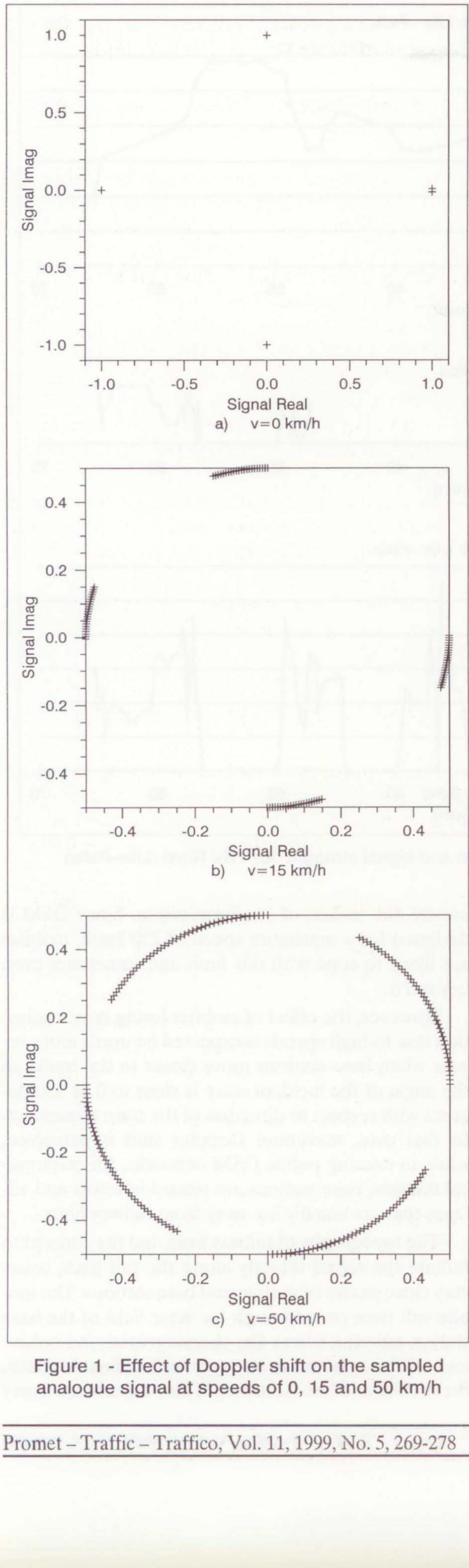

Figure 1 - Effect of Doppler shift on the sampled analogue signal at speeds of 0, 15 and 50 km/h

be demodulated correctly. Then the maximum allowable Doppler frequency can be 217 Hz, corresponding to the speed of 250 km/h.

The above considerations and the previous computer simulation results [8] are based on the assumption that the mobile has already synchronised to the signal and is ready to demodulate. But coming closer to the receiver hardware, the question arises:

Will the receiver *always* be able to synchronise to the signal and what are the restrictions with this respect?

The frequency stability of transmitters is specified in GSM Recommendation 11.10 for mobile stations and in GSM Rec. 11.20 for base stations, respectively. For base stations, it is 0.05 ppm, corresponding to 45 Hz at a carrier frequency of 900 MHz. Additionally, the carrier can be offset by approximately 220 Hz due to Doppler shift at 250 km/h. Doubling the allowable speed raises the total figure to almost 500 Hz. This must be within the tracking range of the receiver PLL, otherwise the mobile will not be able to synchronise.

In the test equipment specifications GSM11.10 and GSM11.20, there is no requirement for a mobile to actually perform at a speed of 250 km/h. Implementation of receivers is completely proprietary, so that the performance of different pieces of equipment at high speeds may strongly vary among different manufacturers.

2.1.1 Analysis of Measurement Results

To investigate the susceptibility of synchronisation to increasing the speed, we made measurements in a French TGV high-speed train, particularly TGV Nord for a journey between Lille and Paris. We used a commercial GSM mobile with an interface to connect a laptop PC for monitoring. In Figure 2, the speed profile of this journey is shown, followed by the synchronisation information (number of detected neighbouring cells) and the signal strength, reported by the mobile station.

When the speed of the train reaches 300 km/h (the minutes 10, 20 and 50), the mobile does not report any signal from the serving cell. This may be caused by either:

- no radio coverage,
- loss of synchronisation due to excessively high speed,
- internal software error in the mobile.

Notice the sudden gap in signal strength and synchronisation information for the period between the minutes 50 and 60. Although the received signal level is rather high immediately before and after the gap, the mobile cannot find any signal for the period of high speed. It seems that the mobile falls out of synchronisation as soon as the train goes faster than 270 km/h and catches back on, when the train slows down again.

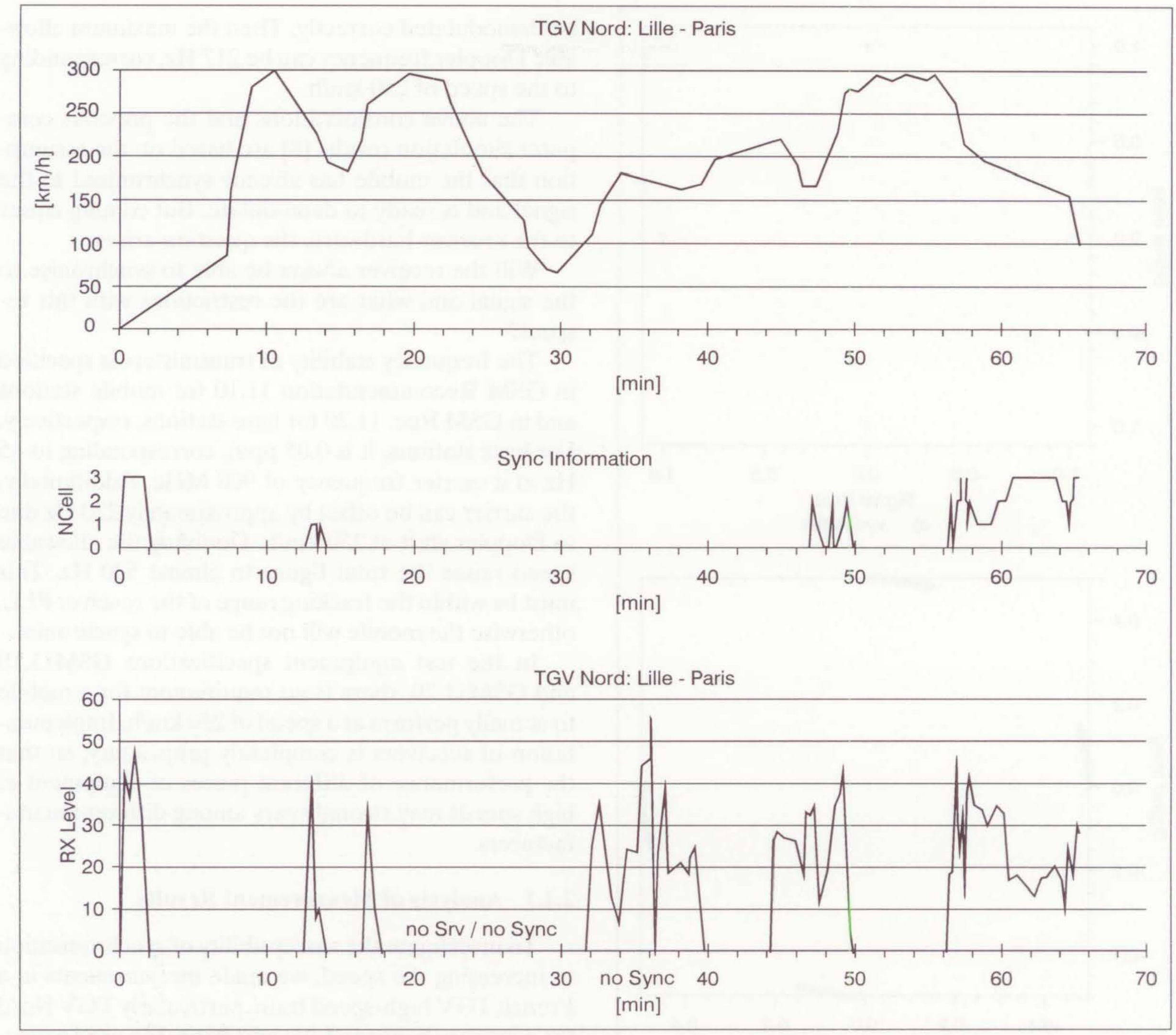

Figure 2 - Speed profile, synchronisation information and signal strength for TGV Nord (Lille-Paris)

A similar experiment repeated in the TGV Sud-Est line from Paris to Lyon (Fig. 3) did not show the complete dropout as on the Lille-Paris line. This might be because TGV Sud-Est with maximum speed of 270 km/h runs slightly slower than the TGV Nord.

Rather, we noticed on several occasions that during the periods of high speed, the mobile could keep track of its own carrier, but did not succeed in correct decoding of the neighbouring cells. This was especially evident around the minute 80 of the journey. The "System Information" messages on the serving cell's BCCH carrier [7] were usually coming cyclically in packets of four messages and were displayed on the PC roughly every 4 seconds.

During periods of high speed, it was noticed that the messages were no longer coming cyclically, but as single ones in random order at a rate of 1 message every 40-60 seconds. This can be interpreted as if the mobile station was just at its performance limit, sometimes succeeding in decoding a message and failing mostly due to loss of synchronisation. Since GSM is designed for a maximum speed of 250 km/h, mobiles are likely to cope with this limit and sometimes even beyond it.

However, the effect of mobiles losing synchronisation due to high speeds is expected be much more severe when base stations move closer to the tracks as the angle of the incident wave is close to 0 or 180 degrees with respect to direction of the train movement. In that case, maximum Doppler shift is perceived, while in existing public GSM networks, for economical reasons, base stations are placed in towns and villages that are usually far away from railway lines.

The topography of railway lines and the concept to radiate the signal directly along the rail path, cause very close passes of mobile and base stations. The mobile will then pass through the near field of the base station antenna where the characteristics and behaviour of the antenna is not very well definable. Both, the mobile and base station will also experience a very

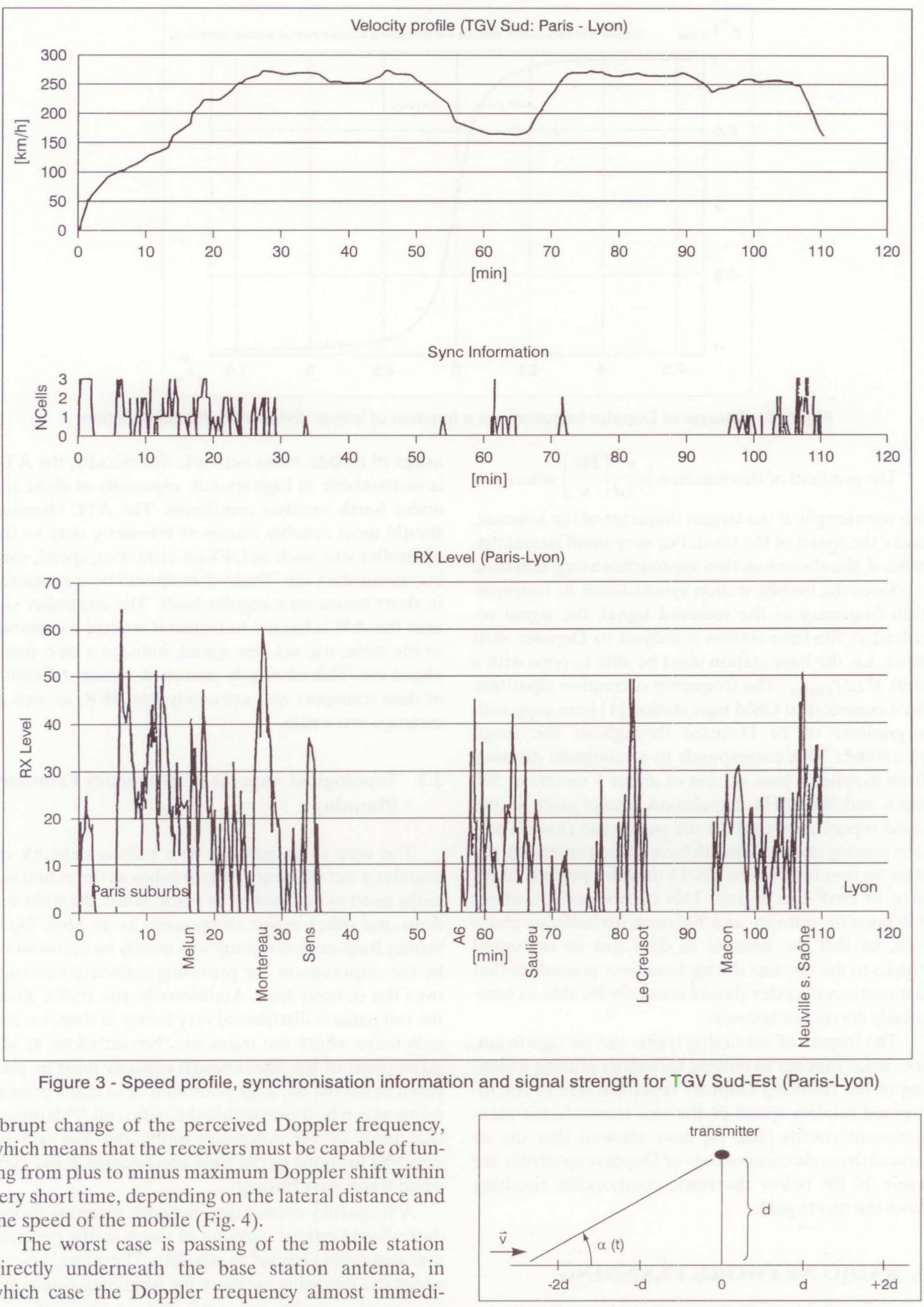

Figure 3 - Speed profile, synchronisation information and signal strength for TGV Sud-Est (Paris-Lyon)

abrupt change of the perceived Doppler frequency, which means that the receivers must be capable of tuning from plus to minus maximum Doppler shift within very short time, depending on the lateral distance and the speed of the mobile (Fig. 4).

The worst case is passing of the mobile station directly underneath the base station antenna, in which case the Doppler frequency almost immediately jumps from its +maximum to its –maximum (Fig. 5).

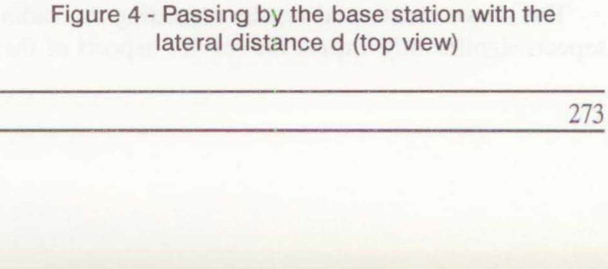

Figure 4 - Passing by the base station with the lateral distance d (top view)

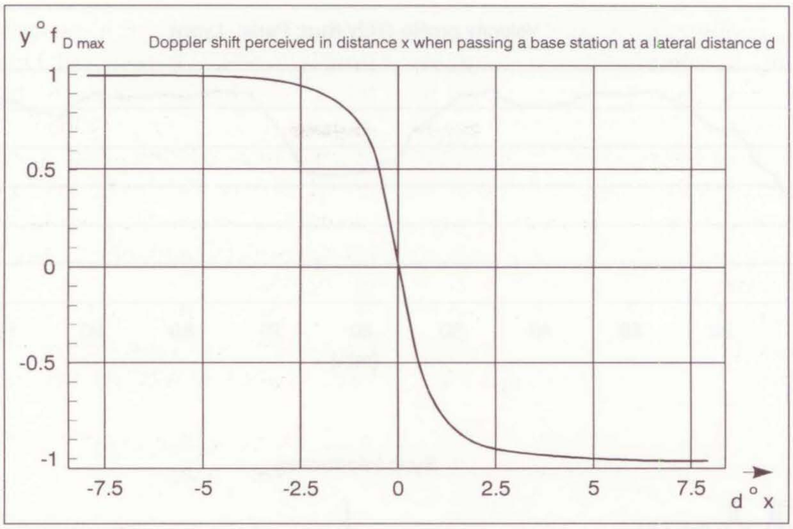

Figure 5 - Change of Doppler frequency as a function of lateral distance to the base station

The gradient of this function is $\frac{v^2}{\lambda d}\left[\frac{\text{Hz}}{\text{s}}\right]$, where λ is the wavelength, d the largest diameter of the antenna, and v the speed of the train. For very small lateral distance d, the above function approaches a step function.

Since the mobile station synchronises its transmission frequency to the received signal, the signal received at the base station is subject to Doppler shift twice, i.e. the base station must be able to cope with a shift of $\pm 2f_{D\max}$. The frequency correction algorithm for a commercial GSM base station [11] can cope with a gradient of 12 Hz/msec throughout the range $f_0 \pm 500\text{Hz}$. This corresponds to a minimum distance from mobile to base station of about 5 meters at 500 km/h and 900 MHz. Simulation results given in the same report show that for the worst case (mobile station passing exactly beneath base station antenna), the base station receiver needs 34 timeslot periods to return to error-free signal. This corresponds to about 150 msec for full-rate and 300 msec for half-rate channels, so that the amount of data lost or corrupted equals to the one lost during handover procedure that the receiver decoder should normally be able to completely correct or recover.

The impact of oncoming trains can be significant, too, since they act as moving reflectors causing widening of the resulting Doppler spectrum due to the increased relative speed of the two trains. Some measurement results [10], [4] have showed that the so caused dynamic components of Doppler spectrum are some 20 dB below the static components resulting from the direct path.

3. RADIO NETWORK PLANNING

The above mentioned results regarding the radio aspects significantly impact the service aspects of the usage of mobile radio network. Specifically, the ATC is unavoidable at high speeds, especially at night and under harsh weather conditions. The ATC channels should most reliably transport telemetry data to the controller site, such as GPS co-ordinates, speed, various status data etc. These data should be transmitted in short bursts on a regular basis. The controller site uses the ATC channel to transmit control commands to the train, e.g. set new speed, indicate a stop signal ahead etc. This obviously presumes utmost reliability of data transport and extremely low BER, as well as message error rate.

3.1 Topological Aspects of Frequency Economy Planning

The area to be covered by a railway network resembles a net with very large meshes as the actual rail paths need to be covered as a line, while the train stations and other major compounds as an area. Optimising frequency economy will mostly be constrained by the requirement for providing sufficient coverage over the desired area. Additionally, the traffic along the rail paths is distributed very bursty in time, i.e. it is only there where the trains are. Nevertheless, at any given point of the line, enough capacity must be provided to handle the load generated by as many passing trains as can be found within the radio cell. This means that most of the resources along the line will be stand-by for most of the time and become active only when trains pass through.

A frequency-economical network planning procedure should enable carrying as much traffic per area unit and radio channel as possible. Therefore, we can adopt the following measure for frequency economy:

$$\eta_f = \frac{\textit{traffic}}{\textit{area unit} \cdot \textit{radio channel}}\left[\frac{\text{Erlang}}{\text{km}^2\text{MHz}}\right] \tag{2}$$

This implies that, if observing a single cell, economical usage can only be achieved for large traffic, since cell area and at minimum one radio channel to be installed, cannot be varied. However, if observing a whole network, this can be improved by re-using the same set of radio channels in as many different cells as possible which reduces the overall amount of used spectrum resources.

Assuming a small urban cell (area $\approx 0.5\,\text{km}^2$) with 4 GSM carriers (approx. 23 Erl), η_f is in the order of:

$$\eta_f \approx \frac{23}{0.5\cdot(4\cdot 0.2)}\left[\frac{\text{Erlang}}{\text{km}^2\text{MHz}}\right] \approx 55 \div 60\left[\frac{\text{Erlang}}{\text{km}^2\text{MHz}}\right] \quad (3)$$

In a railway environment, the traffic along the lines is expected to be rather low, while the area may be large. Consequently, the overall achievable η_f will not be very satisfying. Therefore the term "frequency economy" in this context can rather stand for optimised use of radio resources under the constraint of required full line coverage.

Since railway lines run in rather large distances from each other, mutual influences in radio and frequency planning can be neglected so that each line can be separately covered with a few frequencies only, possibly needing some more at junctions and crossovers. Railway stations and other railway-owned compounds forming nodes or distinct islands within the network, can be covered with some extra radio channels, depending on network configuration and traffic load.

3.2 "Off-line Seamless Handover"

3.2.1 Standard GSM Handover

A mobile engaged in a call is handed over to the appropriate neighbouring cell without noticeable interruption of the ongoing call by means of a process occurring in the fixed network called "handover" in GSM, or "hand-off" in some other radio systems. In GSM the handover is "mobile assisted", which means that the mobile station continuously reports to the network the identifiers of neighbouring cells it can receive with a useful signal level. The network then decides when exactly and to which of the neighbouring cells the mobile will actually be handed over. The process of handover is specified in GSM Technical Specification 03.09 [12], as the message flow for the general case of handover between cells connected to different base station controllers (BSC). The time interval between the instant of the decision (taken by the network) for the handover and the message "handover complete", marking the end of the handover process, is around 1200-1400 msec. The time the mobile station needs to tune to the new physical channel in frequency and timing, to asses the radio parameters on the new channel and to establish the link to the new base station, is around 500 msec [10]. During this time the mobile station has no link to the base station at all, the only rescue line being a fallback opportunity to the old channel in case a link in the new cell cannot be established. In case the conditions on the old channel have meanwhile deteriorated so much that the mobile cannot re-establish the link on the old channel either, the call is lost.

In high-speed railway environment, the risk of a failing handover must be minimised, since trains will be controlled by ATC via the radio link.

3.2.2 Proposal for an Off-line Handover Mechanism

All traffic generated within a train is assumed to be collected and trunked in the train. It is then fed to a transceiver unit, which transmits the resulting data stream towards the base stations along the tracks. This transceiver unit can be regarded as a "multiple mobile station", carrying several active calls simultaneously. These various data streams are e.g.:

- ATC,
- driver-to-controller voice channel,
- group call to train staff,
- passenger information service,
- various calls from/to passengers.

The traffic load from a passing train on to a base station is considerably higher than that from a standard mobile station. As all of the calls must be handed over *simultaneously*, all needed resources must be allocated at the base station within very short time. The risk of unavailable resources increases with the number of ongoing transactions. A priority indication allows ranking of the calls to make sure the most important calls are served first in case of lacking resources.

Modern high-speed trains usually consist of a number of cars flanked by an integrated propulsion unit at both ends. Assuming these are equipped each with a directional antenna on their facing ends allows utilising a new kind of diversity mechanism which reduces the risks involved in handover.

The mobile station should consist of two separate transceiver functions located at each end of the train. Each one maintains a link to a different base station. This allows us to define and propose a new type of handover – the Off-line Seamless Handover (Fig. 6).

A train, having just passed a base station, maintains all its radio links via the rear transceiver towards the base station just passed. Meanwhile, the receiver at the front end searches for the signal of the new base station ahead. Having found a suitable one, it establishes a contact with the new base station and announces the number and the type of resources needed for a full handover. The resources are allocated by the

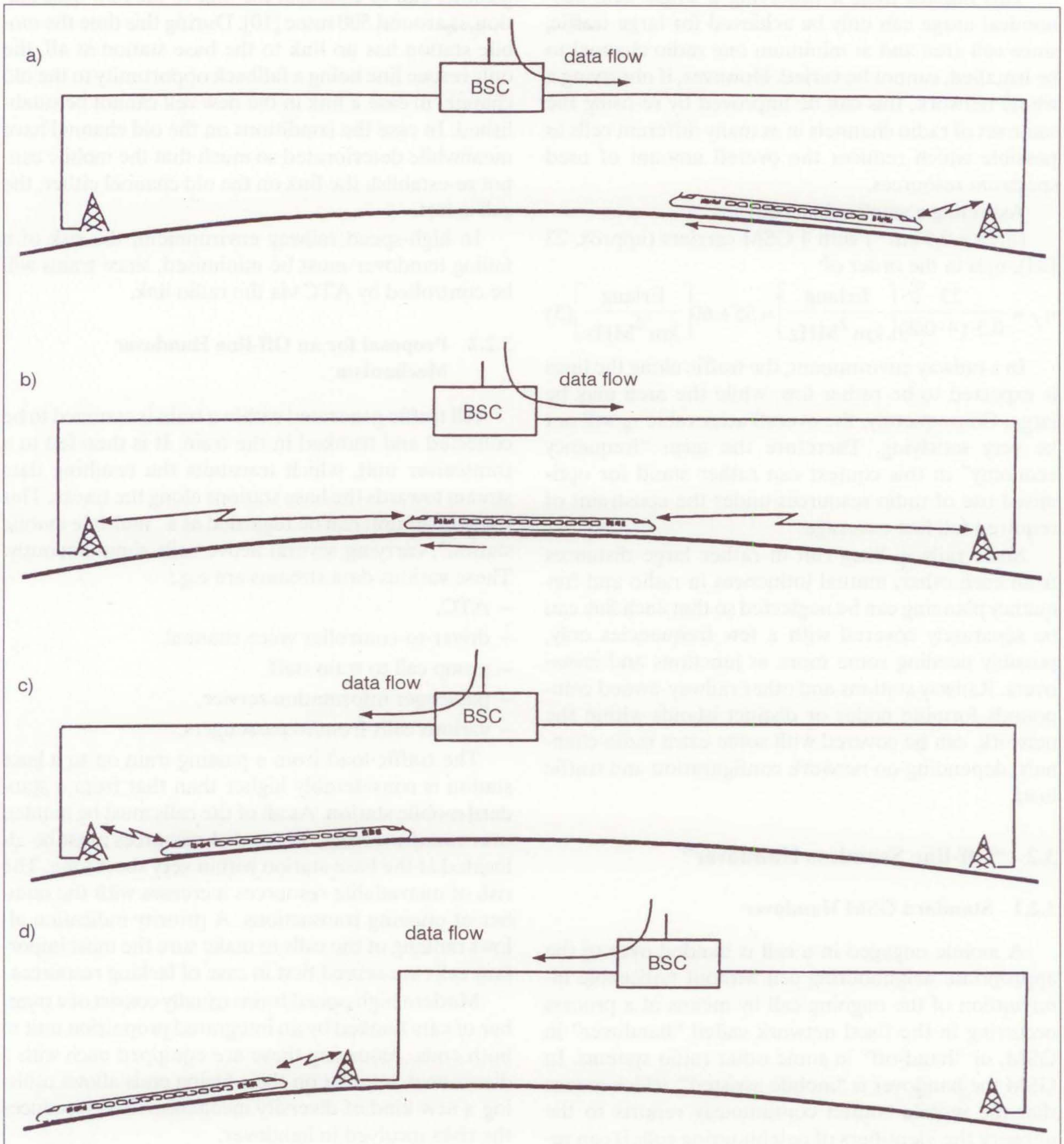

Figure 6 - Principle of the Offline Handover method

a) train keeps link via the rear transceiver while front transceiver searches for next cell
b)synchronised to new cell; train keeps link via the rear transceiver while front receiver negotiates resources needed with the new cell
c) handover to the new cell: link to old cell is released
d) signal is switched from front to rear transceiver near the base station (when signal is stable and high)

base station according to its priority listing. This procedure is not very time-critical; it can happen in off-line mode and take several seconds. When the new link is fully allocated, an established call temporarily occupies the resources actually needed. Now the Seamless Handover can take place: In both network and mobile station, the data stream between the old base station and the rear transceiver is simultaneously switched via the new cell to the front transceiver. Since the new link is completely established, there is no need for additional frequency and timing adjustments, and consequently no need for interruption of the actual data transmission. The handover achieved by this method is completely seamless and rather uncritical in timing, hence the term "off-line".

A drawback of using Off-line Handover method is obviously the necessary large overlap area between neighbouring cells. Assuming that the resource allocation in the new cell is completed within 4 seconds, a train at 500 km/h would travel almost 600m in distance. Considering the flat open environment (the only one in which such vehicle speeds are feasible), achieving this overlap distance however, does not seem unrealistic.

A standard GSM handover procedure also includes an observation time of several seconds, in which the network observes a number of neighbouring cell measurements from the mobile in order to determine the most appropriate handover partner cell. Since trains run along predictable paths, the handover partner is always known in advance and the observation time can be omitted.

4. CONCLUSION

The impact of Doppler shift on GSM susceptibility to synchronisation loss has been experimentally investigated for high-speed trains running at currently limited speeds of up to 300 km/h. It has been found that legacy GSM systems show some even larger margin than it might be expected according to GSM specifications (limited to speeds up to 250 km/h). However, unlike legacy GSM base stations, mostly situated in cities far away from railway tracks, for reasons of frequency economy and better radio coverage, base stations, dedicated to railways, will most likely be much closer to the tracks. This will make the susceptibility to sync loss due to Doppler shift much more significant. Moreover, since high-speed trains will be controlled via ATC over the radio link, the overall reliability of the radio communication system must be far better than with the conventional GSM technology in this environment. Specifically, the risk of a failing handover must be minimised. Therefore, a new type of handover – the Off-line Seamless Handover has been defined and proposed here. In this algorithm, the mobile station consists of two separate transceiver functions located at each end of the train, where each one maintains a link to a different base station.

SAŽETAK

NEKI ASPEKTI PROPAGACIJE SIGNALA I PREUZIMANJA PROMETA MOBILNOG RADIO SUSTAVA KOD VLAKOVA VELIKIH BRZINA

Nekoliko europskih zemalja počelo je izgradnju brzih željezničkih linija sa brzinama oko 300 km/h, za koje se očekuje da će, u ne tako dalekoj budućnosti, postati okosnica putničkog prijevoza na srednjim linijama. S tim u vezi je prije nekoliko godina Unija europskih željezničkih operatora (UIC) donijela odluku o izgradnji nadnacionalne mreže mobilnih komunikacija koja se bazira na GSM tehnologiji i njenim dobro poznatim osobinama (kao što su npr. za korisnika transparentno preuzimanje poziva i sl.), kojima su pridodate i neke nove značajke kao što su npr. grupni pozivi i uspostava prioriteta usluge. Naime, sa gledišta propagacije signala, zbog brojnih prepreka kao što su npr. tuneli i usjeci, prijam signala vanjskog konvencionalnog GSM predajnika može biti veoma otežan, pa pojačala koja bi se ugradila na vlaku trebaju imati vrlo veliki dinamički opseg. S druge strane, zbog imperativa korištenja mobilnog sustava i kao komunikacijskog kanala za automatsko upravljanje vlakom (vitalno za ove brzine), zahtijeva se visoka pouzdanost ove veze, što automatski eliminira korištenje konvencionalnog GSM, koji je predviđen za brzine do maksimalno 270 km/h, jer na većim brzinama Dopplerov pomjeraj noseće učestalosti postaje glavna smetnja i nezaobilazni ograničavajući faktor, čiji je utjecaj na gubitak sinkronizacije (a time i intenzitet otkaza, tj. pouzdanost komunikacijskog sustava) ispitivan eksperimentalno na graničnim brzinama do 300 km/h. S druge strane, poseban problem ovdje predstavlja preuzimanje poziva. U radu je predloženo rješenje u vidu relativno jednostavnoga off-line algoritma.

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