Evaluation of the Quality of the Wi-Fi Channel of the Rolling Stock Network

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Abstract: The paper presents the results of research on the quality of the Wi-Fi channel used for technical monitoring of the condition of rolling stock and railway transport infrastructure. For this purpose, a method has been developed for calculating the probability of an error in the Wi-Fi channel between stationary base stations and mobile in local network of the train, taking into account the features of modulation formats and experimental data on communication quality. The presented methodology is based on the analysis of the effect of slow and fast fading of the signal at the receiver input during the movement of the train, which lead to deep channel speed dips. The reliability of the channel quality estimates obtained using the presented methodology is confirmed by the results of calculating the error probability based on the processing of experimental data.

1 INTRODUCTION

Currently, information transmission systems based on Wi-Fi technology are widely used in railway transport for the implementation of technical monitoring of rolling stock and infrastructure facilities. The main advantage of Wi-Fi technology is the possibility of two-way information exchange and constant monitoring of the infrastructure without deterioration of the electromagnetic environment. With the help of a network of base stations (BS) deployed along the railway track, technical monitoring data can be sent to car depots, marshalling yards, centralized traffic control and safety center (Popov, 2020).

To organize monitoring using Wi-Fi technology, it is necessary to assess the quality of the channel between stationary and train base stations. The solution of this problem is connected with the development of a methodology for calculating the probability of error P_{err}., taking into account the peculiarities of the propagation of decimeter range signals and the modulation formats used.

Thus, as a result of interference of reflected waves at the receiver input and changes in the level of the desired signal during the movement of the train, slow fading (s/f) and fast fading (f/f) of the envelope of the carrier signal occur. This leads to dips in the signal-to-noise ratio (s/n) and a deterioration in the quality of communication. To combat these phenomena, stationary BS (SBS) and train BS (TBS) are periodically switched – handover and correction of the modulation format: code positionality a(from 4 to 1024) and the type of modulation (BPSK, QPSK, QAM), the encoding rate k/s (from 1/2 to 5/6), the protective interval (cyclic prefix from 400ps to 800ps), the number of spatial streams from 1 to 4 (IEEE 802.11ax, 2022; Denisov, 2019)

2 MATERIALS AND METHODS

As shown by experimental data obtained from the input of the TBS (MaximaTelecom, 2021; Antonov, 2022; Zhuravleva, 2022), the consequence of the occurrence of s/f and f/f are adaptive changes in the modulation format, which lead to sharp dips in channel speed (c/s) and relatively long fluctuations in c/s ranging from 700Mb/s to 60Mb/s and below (fig. 1). The consequences of handover, fluctuations and sharp failures of the c/s directly affect the efficiency and quality indicators of Wi-Fi technology, and above all, increase the probability of errorP_{err}.

So, the fading of the signal at the input of the demodulator (DM) of the receiver under the action of s/f and f/f should be evaluated using parameters in the form of the ratio of signal power and noise (s/n): a) for slow fading through $\alpha^2_{s/\mathrm{f}}$(relative to the sensitivity

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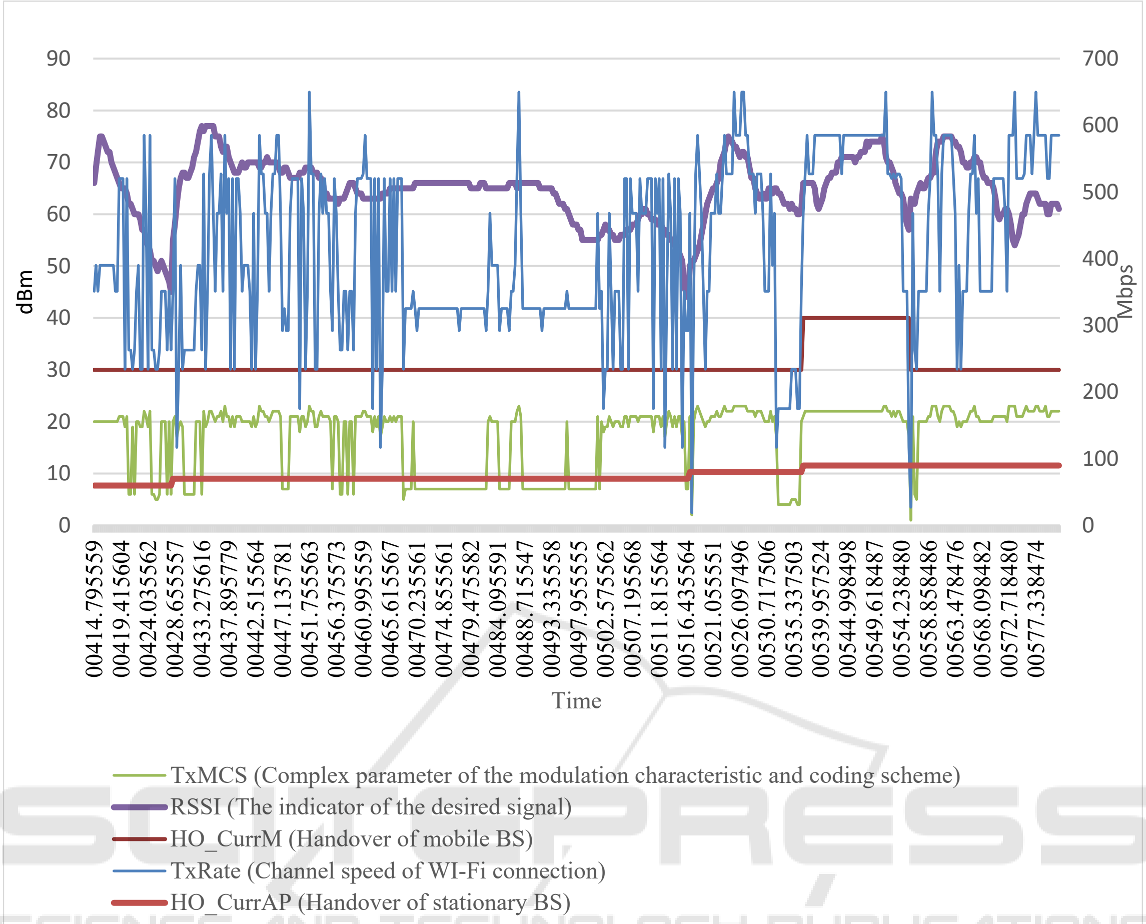

Figure.1. Experimental characteristics of the functioning of the channel between the SBS and the TBS of the Wi-Fi network.

threshold of the receiver); b) for fast fading through $\alpha_{f/f}^{2}$ (relative to random fluctuations of the carrier envelope) (Ratynsky, 1998).

A decrease in the signal level during the movement of the train ($\alpha_{s/f}^{2}$) and fluctuations in the envelope ($\alpha_{f/f}^{2}$) as a result of the reflected signals lead to abnormal errors. The moments of error occurrence are marked in Fig.1 by sharp dips or fluctuations in c/s at the output of the channel decoder, which reacts to the deterioration of signal propagation conditions. The magnitude of the probability of an abnormal error$\mathrm{P}_{\text{ан}}$, meaning an error in at least one character, depends on the values $\alpha_{s/f}^{2}$and $\alpha_{f/f}^{2}$ (Gorelov, 2013). As a result of adaptive correction of the modulation format, for example, a decrease in positionality awith a decrease in s/n, it is possible to maintain the quality of communication P_{err} at a given level at the cost of a sharp decrease in the information transfer rate.

3 RESULTS AND DISCUSSIONS. METHODS FOR ASSESSING THE QUALITY OF THE WI-FI CHANNEL

The method of calculating the error probability P_{err} of channel quality is based on the analysis of experimental data on the operation of the train's Wi-Fi channel and the assessment of anomalous distortions of the desired signal from the action of s/f and f/f. Abnormal symbol errors occur due to fluctuations in the signal envelope at the output of the demodulator (DM), which lead to time shifts (Δt) of the pulse position within its interval (Fig.2) (Fomin, 1975).

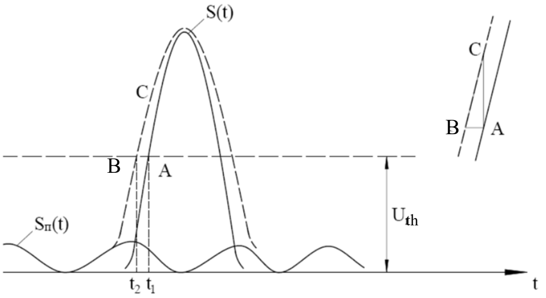

Figure 2. The mechanism of formation of time shifts of the symbol due to envelope fading: and, accordingly, the envelope of the pulse and noise from f/f; and the moments of operation at the level (points A and B) accordingly, in the absence of noise and with noise.

If the value Δt exceeds the protective interval (cyclic prefix $\tau_{c/p}$), an error of false symbol discrimination will occur. With the threshold DM algorithm (as the simplest in technical implementation), the first emission of the signal envelope beyond the boundaries of the interval is triggered. Thus, an abnormal error will occur if two conditions are met: 1) the magnitude $\Delta t > \tau_{c/p} \Delta t \succ \tau_{c/p}$; 2) the amplitude of the symbol $A_s > V_{th}$. The fulfillment of the first condition is estimated by probability $P(\Delta t > \tau_{c/p})$; the second – by the probability of false triggering$P_{л/ср}$. To calculate the probability $P(\Delta t > \tau_{c/p})$, knowledge of the elementary probability law (EPL) of envelope fluctuations due to f/f is required. Noise or distortion of the envelope from f/f is the result of interference (the superposition of many reflected rays of a desired signal having different initial phase and amplitude). Therefore, the EPL law of random fluctuations of the envelope corresponds to the normal law (Wentzel, 1983). The magnitude of the variance of these fluctuations σ_h^2 can be determined on the basis of experimental data using the 3- sigma rule. So, taking into account the sensitivity of the TBS receiver $p_{r/s} = -95\ dBm$, the average value of s/n $\alpha_{s/f}^2$= 65 *dBm* and the magnitude of the fluctuations of the parameter $\alpha_{б/з}^2(\pm 5 dBm)$, the noise dispersion is equal to: $\sigma_h^2 \cong 10^{-12}$Вт.

Time shift Δt (of the pulse) of the symbol is a random variable, which is also distributed according to the normal law, since it is a consequence of the impact of noise from f/f. The variance $\sigma_{\Delta t}^2$of the time shift is determined through the variance σ_h^2 and the steepness of the pulse $D_s$at the threshold level V_{th} as follows (Gorelov,2013; Fomin, 1975):

$$\sigma_{\Delta t}^2 = \frac{\sigma_h^2}{D_s^2}. \tag{1}$$

For angles (between threshold and envelope) at a level $V_{th} \approx \frac{A_s}{2}$close to the maximum steepness of the pulse 890, the variance of the time shift Δtwill be the value $\sigma_{\Delta t}^2 \cong 0{,}3 \cdot 10^{-15}$.

The probability $P(\Delta t > \tau_{s/p})$ for $\tau_{s/p} = 400\ ps$ (IEEE 802.11ax, 2022; Denisov, 2019) is calculated from the expression:

$$P(\Delta t > \tau_{s/p}) = \int_{x}^{\infty} \frac{1}{\sqrt{2\pi\sigma_{\Delta t}^2}} epx(-\frac{x^2}{2\sigma_{\Delta t}^2}),$$

$$\text{where } x = \Delta t. \tag{2}$$

Using the tabular integral $V[x]$(complement to the probability integral) (Gorelov, 2013), we obtain the following value for$P\big(\Delta t > \tau_{\text{pref}}\big)$:

$$P(\Delta t > \tau_{ц/пр}) = P(x_1) = \frac{1}{\sqrt{2\pi}} \int_{x_1}^{\infty} \exp(-\frac{z^2}{2}) dz$$

$$\text{where} x_1 = \frac{\Delta t}{\sigma_{\Delta t}} = \frac{0{,}4 \cdot 10^{-9}}{0{,}173 \cdot 10^{-9}} = 2{,}31;$$

$$P\big(\Delta t \succ \tau_{\text{pref}}\big) = 9{,}176 \cdot 10^{-2} \tag{3}$$

The probability of false triggering $P_{f/tqr}$, taking into account the Rayleigh elementary probability law of the envelope at the output of the DM (Gorelov, 2013; Fomin, 1975), is determined by the formula:

$$P_{f/tgr} = \exp(-V_{th}^2 / 2\sigma_A^2), \tag{4}$$

where σ_A^2 is the variance of the signal envelope amplitude.

Based on experimental data of the signal power level spread from s/f (Fig.1) within -45 *dBm* and -25 *dBm* from an average value of -35 *dBm*, the value $A_s^2 = 3{,}162 \cdot 10^{-4}$ and $\sigma_A^2 = 7{,}115 \cdot 10^{-5}$ can be estimated.

Hence, the probability $P_{f/tgr} = \exp(-V_{th}^2 / 2\sigma_A^2) = \exp(-2{,}1) \cong 0{,}122$.

The probability of an abnormal error P_{abn} is:

$$P_{abn} = P(\Delta t > \tau_{c/p}) \cdot P_{f/tgr} \cong 0{,}011 \tag{5}$$

To calculate the probability of error P_{err} when transmitting a frame with the number of elementary characters кof the order of a thousand, it is necessary $P_{ан}$to divide by K, namely:

$$P_{err} = \frac{P_{abn}}{к} = 1{,}11 \cdot 10^{-5} \tag{6}$$

The final value of the Wi-Fi channel quality can be obtained if we take into account the action of the channel decoder, which, due to the block-convolutional code, reduces the probability of error by at least two orders of magnitude (Gorelov, 2013).

It is possible to confirm the correctness of the method of analytical calculation of the error probability proposed above using the results obtained after statistical processing of the data obtained as a result of the experiment (MaximaTelecom, 2021; Antonov, 2022).

Analysis of the nature of fluctuations in the channel speed and the frequency of sharp dips of c/s below 50Mb/s showed that during 1200s, when the train was moving at a speed of no more than 50 km/h, 22 dips of c/s occurred with an average duration of 5ms. Each dip of the c/s is a reaction of the channel decoder to a decrease in s/n due to slow and fast fading in order to "soften" the effect of envelope distortions and reduce the magnitude of the error in character recognition. This interpretation of deep dips of c/s allowed us to calculate the value of the probability of dips of c/s $\mathrm{P}_{c/s}$, namely: $\mathrm{P}_{c/s} \approx 9{,}17 \cdot 10^{-5}$ (IEEE 802.11ax, 2022; Denisov, 2019). Hence, the magnitude of the error probability calculated analytically and the estimate obtained statistically have the sa me order. This indicates the correctness of the task, the validity of the developed methodology and the reliability of the results obtained.

4 CONCLUSIONS

1. The proposed method of calculating the quality of the Wi-Fi channel using the probability of error allows us to evaluate the capabilities of wireless technology for technical monitoring in railway transport.
2. The results of assessing the quality of the Wi-Fi channel, obtained on the basis of experimental data and using the developed methodology, indicate the possibility of using it to calculate the probability of error.
3. The acceptable values of the error probability should be evaluated taking into account the features of monitoring railway transport facilities, for example, a crossing carried out using intelligent video surveillance systems (IVSS).
4. Based on the requirements for the values of the probabilities of false and correct detection of dangerous objects at crossings, it is possible to obtain acceptable values of the probability of error in the Wi-Fi channel used to transmit video surveillance information to the train IVSS recognition device.

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