EVALUATION OF RECEIVED SIGNAL POWER LEVEL AND THROUGHPUT DEPENDING ON DISTANCE TO TRANSMITTER IN TESTBED FOR AUTOMOTIVE WLAN IEEE 802.11AC COMMUNICATION NETWORK

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WLAN IEEE 802.11ac is one of the wireless network technologies that can be used for ITS (Intelligent Transport Systems) needs, in particular for providing vehicle passengers with access to the data transmission network. To evaluate the performance of such automotive wireless access networks, it is necessary to perform experimental measurements. By conducting the throughput measurements in WLAN-based automotive communications testbed, it has been observed that the throughput of the communication channel decreases and the received signal becomes weaker as the vehicle moves away from the wireless access point. The aim of the research is to verify theoretically whether there is a correlation between the received signal power level and the throughput of the communication channel depending on the distance to the transmitter. To calculate the received signal power depending on the distance to the transmitter, a log-normal signal propagation model can be used, which takes into account random signal fluctuations that are described by the Nakagami distribution. Further, based on the obtained results, Shannon's theorem can be used to calculate the maximum theoretical throughput of the communication channel. The analysis of the obtained results shows that a correlation exists between the received signal power level and the throughput of the communication channel depending on the distance to the transmitter. The performed theoretical calculations justify the experimentally obtained results.

Keywords: *Experimental results, IEEE 802.11ac, received signal power level, theoretical Nakagami distribution, throughput.*

1. INTRODUCTION

The throughput is a measure of how much data traffic is successfully received at the intended destination per unit of time. The throughput achievable at different layers of the OSI (Open System Interconnection) model varies. In Section 4, the term “throughput” is applied either to communication channel maximum throughput, which is equivalent to the system capacity [1] and is measured at the physical layer [2], or the term is applied to the application layer throughput, which is called goodput, and is accordingly measured at the application layer [3]. In case the term “goodput” is used, the amount of data considered excludes protocol overhead bits and also retransmitted data packets [3]. In turn, when determining the capacity of a communication channel, the overheads introduced by higher layers are not considered. Often, the term “throughput” is also used in a general context without mentioning the specific OSI layer where it is measured, or it is applied to transport layer throughput. The term “throughput” is also used in a general context in this article.

In vehicular communication networks based on the WLAN (Wireless Local Area Network) IEEE 802.11, a movement speed of mobile client corresponds to a vehicle driving speed. The average individually achievable throughput of such mobile clients will be lower compared to the standard stationary or nomadic WLAN client. The difference in average performance to be achieved is mainly related to the different moving speeds of clients. As a vehicle speed increases, the mobile client is forced to perform more frequent handover procedures between wireless access points (APs). Consequently, the active data transmission time in AP coverage area decreases and

proportionally more time is spent on the organisation and execution of the handover procedure [4]. Another important reason for the decrease in average throughput is the impact of environment on wireless data transmission, which becomes much more aggressive, compared to standard client movement conditions. At higher velocities, radio waves are reflected more intensively, and various and rapidly changing sources of external interference are possible. This increases a probability that client data may be lost or corrupted, which in turn means that the lost data will need to be retransmitted. As a result, application layer throughput (goodput) decreases as overheads increase [3]. This may also lead to an increase in the delay of handover procedure [4]. When assessing the theoretically possible throughput of a communication channel, it is important to consider both the distance between the mobile client and the transmitter, and the possible multipath propagation of signals. The theoretically obtained results can be compared with the experimentally obtained data; thus, the used mathematical models can be verified. The obtained results can also be used to improve the handover algorithms of the mobile client, where the fluctuations of the received signals would be considered.

This paper is organised as follows. Section 2 provides an overview of related works. In Section 3, we evaluate signal power level dependence on the distance to the transmitter with and without signal fluctuations. Section 4 provides the evaluation of throughput dependence on the power level of the received signal and the distance to the transmitter. Concluding remarks are presented in Section 5.

2. RELATED WORKS

In several studies, the power level of received signal *RSS* (Received Signal Strength) in the WLAN (also referred as WiFi) [5] is estimated depending on the distance to the transmitter. Estimates were performed both theoretically, for example, using two-ray flat-earth, free-space path loss or log-normal models [6], [7], and experimentally by performed *RSS* measurements [8], [9]. In practice, such multipath propagation causes fluctuations in the power of the received signal. This should be considered when assessing the WiFi network throughput theoretically, because

these power fluctuations directly affect system performance, i.e., throughput. The study [10] proposes a model for estimating the capacity of several competing IEEE 802.11 systems based on radio wave propagation theory and the Shannon's theorem. However, it is not known how the channel throughput theoretically could change depending on the distance to the transmitter, considering the signal fluctuations. Such a relationship would allow comparing theoretically the calculated throughput data with the experimentally obtained data.

3. SIGNAL POWER LEVEL DEPENDENCE ON THE DISTANCE TO THE TRANSMITTER

As a mobile client moves between Wi-Fi network coverage areas, the association with corresponding wireless AP is established. In Fig. 1, the experimentally observed relationship is shown between the power level P of received signal (where *RSS* parameter is used), and the distance to the wireless access point, r . The figure shows a mobile client that is moving from AP-1 towards next wireless access point AP-2. P_{d0} is the minimum distance from the client to the AP-1 and P_{TH} is the threshold, at which the mobile client executes a handover procedure to the next AP. It has been observed that as the mobile client moves away from the AP, the power level of the received signal decreases. It has also been observed that the power level of P or *RSS* signal not only decreases, but also fluctuates around its average value.

Experimental measurements showed that rapid fluctuations in the *RSS* power levels of the received signal caused irreg-

ular (shifted in time) initialization of the handover procedure. It can be executed either too early or with delay, depending on when the P_{TH} or RSS_{TH} value is exceeded. The same applies to the Wi-Fi connection establishment at the initial phase of the measurements. Therefore, when developing handover algorithms, such signal fluctuations must be considered to ensure a correct operation of handover algorithms. Similar experimental observations and related problems have also been described in the study [11].

In this subsection, it is planned to make sure that the experimental observations correspond to the results of theory and other studies [5], [12], [13]. Thus, theoretically the relationship between the changes in the signal power level and the distance to the transmitter will be determined. The data will also be needed in further calculations to determine the maximum theoretical communication channel throughput (capacity).

Fig. 1. RSS parameter changes depending on the distance to the transmitter.

The received signal strength describes the received signal power [14].

3.1. Vehicle-to-Infrastructure Communication Channel Model

One of the geometric models of the V2I (Vehicle-to-Infrastructure) communication channel (communication channel between the vehicle and the fixed roadside infrastructure) [15], which takes into account more than one possible signal propagation path, is a two-ray flat-earth model. In this model, the received signal is composed of a directly received signal and a signal reflected from the ground. At short distances, this model gives fast signal fluctuations, because the signal reflected from the ground shifts in and out of phase in relation to the directly received signal. At long distances between the transmitter and the receiver, the direct signal path and ground-reflected signal path become almost the same. According to [15], the boundary between these two areas, d_c is determined by Eq. (1).

$$d_c = \frac{4h_t h_r}{\lambda}, \quad (1)$$

where h_t – height of the transmitting antenna, m (metres); h_r – height of the receiving antenna, m; λ – wavelength, m.

Using Eq. (1) and experimentally obtained data, which are presented in the Table 1, the parameter d_c was calculated, $d_c = 191$ m.

In the two-ray model, random fluctuations are added, the statistics of which depend on the physical scattering of rays in environment, a zero-mean Gaussian distribution is assumed, which gives an acceptable result and is consistent with the results of measurements. This is referred to as a *lognormal* model. The notation of the model in general form is shown in Eq. (2). The model allows determining the power level P of the received signal, depending on the distance r between the transmitter and the receiver. The present research covers the case where signals propagate over short distances, i.e., if [15], [16].

$$P(r) = P(d_0) - 10u \log_{10} \left(\frac{r}{d_0} \right) + X_\sigma, \quad (2)$$

where $P(r)$ – power of the received signal (corresponds to RSS) depending on r , dBm; d_0 – distance from the wireless access point

to the vehicle, m; r – distance between a transmitter and a receiver, m; $P(d_0)$ – power of the received signal, when the client is

directly opposite of the wireless access point, dBm; u – path loss exponent; X_σ – random variables, dB.

Table 1. Experimentally Obtained Data

Parameter	Value
h_t	1.85 m
h_r	1.5 m
λ_v	0.058 m
d_0	3.5 m
$P(d_0)$	−49 dBm
r	3.5–100 m
u	1.9
σ	5.9 dB

The values of the parameters u and σ (where σ – a standard deviation of the random variables X_σ) for the highway case are experimentally obtained in the study [16]

and are given in Table 1. In experimental measurements, both the transmitter and receiver used IEEE 802.11ac standard.

3.2. The Power Level of Received Signal without Fluctuations

Using Eq. (2), the values of $P(r)$ were calculated without taking X_σ into account. Figure 2 shows the obtained relationship

between the power of received signal and the distance from the transmitter to receiver, without signal fluctuations (see a red curve).

3.3. The Power Level of Received Signal with Fluctuations

Due to short distances, which are typical of V2I/V2X (Vehicle to Everything) links, a more accurate description of signal fluctuations is given by small-scale fading models, where the fluctuations are caused by constructive and destructive interference between the components of multipath signal propagation. If the in-phase and quadrature components of the signal fluctuate as independent random variables with the Gaussian distribution, the results of *Rayleigh* or *Rician* statistics are provided, depending on whether there is a line of sight. The distribution of the received signal that can be used to model both types of statistics is the Naka-

gami distribution (3).

$$f(x; \alpha, \omega) = \frac{2\alpha^\alpha x^{2\alpha-1}}{\omega^\alpha \Gamma(\alpha)} e^{-\frac{\alpha x^2}{\omega}}, \quad (3)$$

where α is a shape parameter; ω is an estimate of average power in the fading envelope; x is a general random number that is exposed to the Nakagami distribution.

If $\alpha = 1$, the Nakagami distribution describes a *Rayleigh* distribution, and if $\alpha > 1$, it is the *Rician* distribution. The average value of the fluctuations of the received signal power is calculated as follows:

$$\bar{X}_\sigma = \int_0^\infty x f(x; \alpha, \omega) dx = \int_0^\infty x \left(\frac{2\alpha^\alpha x^{2\alpha-1}}{\omega^\alpha \Gamma(\alpha)} e^{-\frac{\alpha x^2}{\omega}} \right) dx. \quad (4)$$

In the calculations ; thus, Eq. (4) is simplified:

$$\bar{X}_\sigma = \int_0^\infty \frac{2x^2}{\omega} e^{\frac{-x^2}{\omega}} dx. \quad (5)$$

Equation (5) was used to determine the effect of fluctuations of the input signal on $P(r)$ (2). In calculations we used $\omega = 1$. Initially, the average value of power fluctua-

tions was calculated. Then, random values with Gaussian or Normal distribution were generated, where we used the obtained values and the experimentally obtained standard deviation σ for the random sample variables , which corresponded to the highway scenario (Table 1), [16].

Figure 2 shows the obtained results (see a blue curve).

Fig. 2. Theoretically calculated power of the received signal depending on the distance to the transmitter without P fluctuations and with P fluctuations.

4. THROUGHPUT DEPENDENCE ON THE POWER LEVEL OF THE RECEIVED SIGNAL AND THE DISTANCE TO THE TRANSMITTER

The Shannon's frequency channel capacity theorem (Shannon's theorem) is used to calculate the upper limit of data transfer rate of communication channel or the channel capacity C (bit/s) (6). It describes the physical layer throughput, which makes it possible to estimate the maximum theoretically obtainable throughput [2], [17]. It represents the ideal system with Gaussian noise [18], [19], where the bit error rate can be reduced to zero by applying appropriate coding schemes, if the user data transfer rate is lower than the channel capacity. However, such codes have not yet

been developed, which is one of the reasons why in practice the obtained data transfer rates are several times lower.

$$C = B \log_2 \left(1 + \frac{S}{N} \right), \quad (6)$$

where C – the capacity of frequency channel, bit/s; B – frequency channel bandwidth, Hz; S – the average power of the received signal in channel, mW; N – the average power of the noise or interference in channel, mW.

By using Eqs. (6) and (2), the theoretical capacity C for an ideal communication

channel was calculated. In calculations, the parameter values $B = 80$ MHz and $N = -90$ dBm were used, where the parameter N was converted to mW. The variable S corresponds to $P(r)$ parameter of Eq. (2).

The calculated channel capacity C , which changes depending on the received signal power level P , with and without the received signal power level fluctuations, is given in Fig. 3.

Fig. 3. Theoretically calculated capacity depending on the power P (dBm) of the received signal without and with power fluctuations.

In addition, Fig. 4 shows the theoretically calculated signal power P in mW, depending on the channel capacity C . The

parameter P was set in the range of 10^{-9} to 10^{-5} mW, which gives practically achievable results.

Fig. 4. Theoretically calculated capacity depending on the power P (mW) of the received signal without power fluctuations.

After that theoretical channel capacity C depending on the distance to the transmitter without and with the received signal power level fluctuations was calculated. Theoretically

obtained capacity and experimentally obtained goodput results are combined in one graph (see Fig. 5).

Fig. 5. Theoretically calculated capacity and experimentally obtained goodput depending on the distance to the transmitter.

In Fig. 5, the depicted green curve represents experimentally obtained goodput, where measurement data are taken from Fig. 6 at the velocity of 50 km/h, in the time interval when the mobile client initially is located opposite the AP and then moves away from it by 100 m (in terms of time

it corresponds to 7.2 s). The experimental measurements were performed with the standard IEEE 802.11ac client. When the mobile client stays directly opposite AP, the client reaches the maximum goodput, as the client moves away from the AP, the distance r increases and the goodput decreases.

Fig. 6. Experimentally obtained goodput at the velocity of 50 km/h.

5. CONCLUSION

The experimentally obtained results, as well as the theoretically calculated data, show that when a mobile client moves away from the transmitter, the power of the received signal decreases and, as a result,

the throughput (capacity and goodput) also decreases. The received signal power is varying and fluctuating in time. The received signal power level fluctuations are caused by constructive and destructive interference

between the components of multipath signal propagation. It should be noted that the newly created graphs (Figs. 3–5) are related to idealization, because Shannon’s theorem [17], [20] is used in the calculations. The theoretical calculations did not consider the client’s speed of movement. The aim of the study has been to make sure whether the experimentally obtained data correspond to the classical conclusions derived from the Shannon’s theorem.

Theoretically calculated wireless channel capacity or the maximum possible throughput is several times higher compared to the experimentally obtained goodput (application layer throughput). The trend and nature of curves are similar, but the absolute values are different. Shannon’s theorem determines a data transferring rate for an ideal channel at the physical layer. It should be noted that experimental measurements in the case of a stationary wireless network client, where the client’s distance to the transmitter would be gradually increased, would give better goodput results compared to a moving client. The

WiFi technology used in the study is able to provide experimentally obtained goodput; it can be seen that there is still a large reserve to the theoretical “ceiling”. Improving debugging algorithms makes it possible to increase overall network throughput.

Higher layers of the OSI model can recognize data only if they are logically designed. Therefore, e.g., the formation of frames, IP packets and ACK messages are required. If a TCP transport protocol is used, it requires additional tasks for transmitting the data. For instance, during the establishment of a TCP session, a three-way handshake procedure is executed, while in the case of packet loss, data are retransmitted. Each OSI layer (from L7 to L2) generates additional traffic or the overhead, such as information about the used application layer protocol (e.g., FTP), TCP header, IP header, Ethernet header and other communication data that need to be transmitted, and this is not considered in the Shannon’s theorem. The performed theoretical calculations justify the experimentally obtained results.

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