Adjacent Channel Interference Analyses in TETRA Direct Mode Operation

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Abstract: - The present paper analyzes adjacent channel interference in TETRA Direct Mode Operation (DMO) for indoor and outdoor environments. To determine minimal stay-away distance and interference area propagation model is used. Thus, a brief overview of free space, Bacon and CEPT SE21 propagation models, mentioned in the TETRA DMO standard is given and two-ray and multi-wall models are described and evaluated by field measurements. We found out, that the two-ray model is suitable for fast estimation of the TETRA DMO signal coverage in open flat area while the multi-wall model, taking into account the attenuation of walls between transmitter and receiver, gives good estimate of the signal levels for indoor applications. Those two models were used for the interference analyses. According to the calculated results two-ray model gives rather pessimistic values of the stay-away distance and interference area in open flat areas while multi-wall model is appropriate for the interference calculation inside buildings that are not surrounded with the high structures causing additional ray reflections back into the interior of the analyzed building.

Key-Words: interference, propagation, path loss, TETRA Direct Mode Operation, two-ray model, multi-wall model, radio signal coverage, stay-away distance

1 Introduction

The analysis of adjacent channels interference strongly depends on the adequacy of the propagation model. In emergency situations reliable radio links between professional mobile users are essential for an efficient execution of rescue missions. Adequate frequency allocation to individual groups must be carefully planned; an appropriate radio signal coverage and sufficient system capacity must be provided to assure efficient communications [1].

The TETRA network usually operates in trunk mode. Since the emergency situations may happen in the areas where the signal strength is low or even in the places without radio signal coverage, an alternative communication mode can be provided, the so-called TETRA Direct Mode Operation (TETRA DMO) [2, 3].

The TETRA DMO enables communication between TETRA terminals without the support of network infrastructure. The DMO is particularly applicable in emergency situations where TETRA signal is not available and where effective local communication among members of rescue team on certain crisis locations is required.

The number of users increases significantly in emergency situations thus enlarging also the possibility of interference between individual users and groups, especially in DMO mode. Therefore, the interference analysis between adjacent channels in TETRA DMO mode has an extraordinary importance in providing reliable and undisturbed communication between professional users.

The propagation model applied for analysis has a fundamental impact on the predicted reliability and efficiency of the DMO communication. Propagation models are an important tool for wireless communication network design. They predict the path loss between the transmitter (Tx) and receiver (Rx), which is the most important information to determine the radio signal coverage and to estimate the interference between adjacent radio channels. Basically, the path loss depends on the carrier frequency, the height of transmit and receive antenna, the propagation environment and the distance between the transmitter and receiver.

The only alternative way to determine the radio signal coverage is field measurements, which are time-consuming and expensive.

The propagation of radio signal for TETRA trunked mode operation is covered in the literature relatively well. Numerous models exist for the calculation of radio signal coverage at 400 MHz frequency band [1]. However, detailed interference analysis and appertaining coverage studies for the TETRA Direct Mode Operation are not available yet. The TETRA standard proposes some short range models for open areas [4] but DMO mode is frequently used in wide open areas (highways and rural environment) where the distances between communication parts exceed one kilometre. Indoor communication presents an additional problem, because of the attenuations caused by walls and floors inside the buildings.

The ray tracing approach using environmental and/or building databases seems to be a good method to predict signal levels; however, the said method is too complex for a rapid estimation of signal level, and also error-prone due to unreliable databases. Therefore, for an efficient and accurate interference analysis in typical environments, where TETRA DMO is frequently used, two straightforward propagation models have been selected and validated by signal strength measurements, namely the two-ray model has been chosen for open flat environments, and multi-wall model has been selected to calculate the path loss inside the buildings [8, 9].

Selected propagation models were evaluated comparing signal levels obtained from the models and those obtained in measurements campaign calculating the absolute mean error (AME) and the root mean squared error (RMSE).

The interference acceptable area was determined based on the calculated stay-away distance for an open flat area and building interior. The influence is also graphically represented as an interference region around the interferer.

The paper is organised as follows: the subsequent section gives a summary of TETRA system and DMO, followed by a section which analyses the interference in TETRA DMO. In the following section propagation models for TETRA DMO needed also for the interference analysis are briefly explained. Two-ray and multi-wall models are described next, followed by DMO signal measurements, which are compared with the simulation results. In Section 6 the interference area and stay-away distance are calculated based on results of path loss models described in previous section. In the conclusion, the intimations for future work are given.

2 TETRA System

TETRA (Terrestrial Trunked Radio) is a set of standards developed by the European Telecommunications Standards Institute (ETSI) [2, 3, 4] that describe a common mobile radio communications infrastructure.

TETRA was developed to meet the needs of public safety and security organisations like police, fire and rescue forces, ambulance services, frontier guards and other professional mobile users [10,11,12].

TETRA has a scaleable architecture, allowing economic network deployments ranging from single site local area coverage to multiple site wide area national coverage.

The performance specifications are optimised for operation between 150 MHz and 900 MHz. Most of the TETRA systems operate in 380 - 400 MHz band.

The spacing between TETRA carriers is 25 kHz. Each carrier provides four independent physical channels applying Time Division Multiple Access (TDMA) technique, which divides carrier into four time slots. The π/4-DQPSK modulation scheme was chosen to support a gross bit rate of 36 kbit/s, which means that net data rates up to 28.8 kbit/s can be offered to some data applications.

The TETRA system was designed for reliable, spectral efficient and safe voice communications and data transmission.

Two main operating modes are defined in the TETRA standard, namely:

- Trunked Mode Operation (TMO) – TETRA V+D; enables basic voice and data transmission in a circuit switched mode using network infrastructure and
- Direct Mode Operation (DMO); enables direct mobile-to-mobile communication without the support of network infrastructure and also mobile-to-repeater communication for the communication range extension.

2.1 TETRA DMO

TETRA Direct Mode Operation enables communication between TETRA mobile users without the use of TETRA switching and management infrastructure (Fig. 1). This mode has been a facility mandated and has been used by many traditional PMR user organizations for several decades.

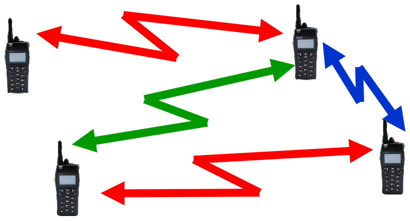

Fig. 1: TETRA DMO

TETRA DMO enables communication also inside the coverage area in the cases of network occupancy or when the connection with the infrastructure is not needed. Besides that, it ensures reliable communication between radio terminals on the edge of the coverage area or outside the coverage of the network infrastructure. Since DMO communication does not need network infrastructure, communication between terminals in the case of network drop out is also possible.

The frequency band assigned to TETRA DMO is different from the frequency band assigned to TETRA TMO. Therefore, there is no need for supervision from the TETRA network side.

Standard TETRA supports several different DMO operating modes:

- 'back-to-back' DMO,
- repeater,
- gateway,
- gateway/repeater,
- managed DMO (MDMO),
- dual watch.

In order not to compromise the reliability and functionality of the TETRA TMO network, the DMO frequency bands are usually planned in the frequency range, allocated for downlink communications, i.e. in the transmit frequency band of the TETRA base station.

3 Interferences in TETRA DMO

In modern cellular telecommunication systems the received radio signal quality is reduced by Gaussian noise and interference caused by terminals in the vicinity. The Gaussian noise influence can be reduced with the sufficient signal level at the receiver, while the interference between base stations can be mitigated with an appropriate network planning.

Given that the TETRA DMO transmitter locations are distributed randomly, the network planning approaches used in cellular systems are not applicable. Thus, only the user behaviour recommendations can be elaborated. Two important types of interference have a significant impact on the quality of the radio connection in TETRA system, namely:

- near/far interference,
- transmitter intermodulation interference.

3.1 Near/Far Interference

Independent of the radio technology every transmitter radiates part of the radio signal power outside the bandwidth dedicated for the communication and disturbs receivers on adjacent frequency bands. The effect is especially expressive in the TETRA DMO where the frequency bands are close to each other. In emergency situation the number of rescue teams using separate frequency bands in the specific area can increase significantly. For the purpose of undisturbed system operation the minimal distances between users of different DMO groups must be determined. Because in some situation where the distance between users is difficult to estimate, for example in the case of the reduced visibility, the influence of near/far interference must be investigated.

Factors which influence the interference level are:

- distance between receiver of group 1 and the transmitter of group 2,
- receiver and transmitter adjacent channel power and broadband noise,
- transmit power,
- frequency separation between communication channels of DMO groups,
- carrier to interference protection ratio (interference level tolerated by the receiver).

Taking into account the above mentioned factors and path loss models, the recommendations concerning minimal distance between terminals in the TETRA system and operation mode of the DMO can be provided to users of the TETRA systems.

3.1 Transmitter Intermodulation Interference

The problem of intermodulation and its solving is well known at radio signal transmission on the base stations of the cellular communication systems. Since DMO transmitters are not stationary, methods for solving intermodulation problems used on base stations are not applicable. Hence, the intermodulation interference depends on the distance between two simultaneously working transmitters and their transmitting frequency bands. Intermodulation interference can be avoided with the planning of the used frequency bands in DMO operating mode in such way that the third harmonic component in chosen frequency band is not present. Due to a poor spectral efficiency of the entire system, the solution is not taken into consideration.

4 Path Loss Models for TETRA DMO

Several empirical radio channel models are available for the VHF frequency band for radio signal propagation prediction in urban, suburban and rural areas as well as for indoor communications; however, their suitability for the DMO mode has not been investigated yet. The TETRA DMO standard [4] recommends three short range propagation models (free space loss (FSL), Bacon and CEPT SE21 model) which are applicable for distances between transmitter and receiver shorter than one kilometre and they are appropriate only for open areas. Therefore, some other models should be applied for longer distances and scattered environments.

4.1 Free Space Propagation Model

The free space propagation model serves as the basic model for understanding more advanced path loss models [5].

The path loss is defined as the ratio between transmitted and received signal power and is defined for free-space propagation as

$$L = 10\log\frac{P_t}{P_r} = 10\log\left(\frac{(4\pi)^2 d^2}{G_t G_r \lambda^2}\right). \tag{1}$$

whereat P_t is transmit power, P_r is receive power, d is distance from transmitter and receiver, G_t is transmit antenna gain, G_r is receive antenna gain and λ is modulated signal wavelength.

In the case of isotropic receive and transmit antennas, previous equation can be rewritten as

$$L = 32.44 + 20\log_{10} f_{[MHz]} + 20\log_{10} d_{[km]}. \tag{2}$$

whereat $f_{[MHZ]}$ is a carrier frequency in MHz and $d_{[km]}$ is distance from transmitter to the receiver in km.

4.2 Bacon Model

The Bacon model is designed for the use in flat, open areas [6]. The model incorporates antenna heights (h_1 and h_2), distance between transmit and receive antennas (d), propagation frequency (f) and percentage of locations where signal level is exceeded (p). The Bacon model defines the basic transmission loss as

$$L = 10\log_{10}(L_1 + L_2), \tag{3}$$

whereat

$$\begin{aligned} L_1 &= 32.4 + 20\log_{10}(fd) + \\ &+ 10\log_{10}(10^{[3-2\log(100-p)]} + 10^{-0.84}), \end{aligned} \tag{4}$$

$$L_2 = L_m + L_c. \tag{5}$$

The term L_m is given by

$$L_m = 120 + 40\log_{10} d - 20\log_{10}(h_1 h_2), \tag{7}$$

while the term L_c is given by

$$L_c = \begin{cases} I(0.01p)\sigma & p > 0.5 \\ I(0.01p-1)\sigma & otherwise \end{cases}. \tag{8}$$

The standard deviation (σ) is defined as

$$\sigma = \begin{cases} \dfrac{L_d}{2.3} & L_d > 0 \\ 0 & otherwise \end{cases}, \tag{9}$$

whereat

$$L_d = L_m - 20\log_{10}(fd) - 32.4. \tag{10}$$

It is also necessary to calculate the minimum value of standard deviation

$$\sigma_{\min} = 2 + 0.1 f^{0.5} \tag{11}$$

and if $\sigma < \sigma_{min}$ then set $\sigma = \sigma_{min}$.

The function $I(x)$ in (8) is defined as

$$I(x) = \xi(x)T(x) = \frac{A(x)}{B(x)}T(x) = \frac{A(x)}{B(x)}\sqrt{-2\ln(x)}, \tag{12}$$

whereat

$$A(x) = [0.010328T(x) + 0.802853]T(x) + 2.515516698, \tag{13}$$

$$B(x) = ([0.001308T(x) + 0.189269]T(x) + 1.432788)T(x) + 1. \tag{14}$$

4.3 CEPT SE21 Model

The CEPT SE21 propagation model was proposed in ITU-R Recommendation SM.329-6 [7]. It is a three segment model, which incorporates antenna heights, propagation frequency and the distance between transmit and receive antennas. The model gives the path loss by

$$L_1 = 20\log_{10} f + 20\log_{10} d + 32.44 \quad d \le 0.04km, \tag{15}$$

$$\begin{aligned} L_2 &= L_1(0.04) + \\ &+ \frac{(\log_{10} d - \log_{10} 0.04)}{\log_{10}(0.1) - \log_{10}(0.04)} \quad 0.04 < d < 0.1km \\ &+ \frac{(L_3(0.1) - L_1(0.04))}{\log_{10}(0.1) - \log_{10}(0.04)} \end{aligned} \tag{16}$$

and

$$\begin{aligned} L_3 &= 69.6 + 26.2\log_{10} f - \\ &-13.82\log_{10}[\max(30; h_{\max})] + \\ &+(44.9 - 6.55\log_{10}[\max(30; h_{\max})])\log_{10} d - \quad d \ge 0.1km \\ &-a(f, h_{\min}) - b(h_{\max}) \end{aligned} \tag{17}$$

whereat the constants a and b are given as

$$\begin{aligned} a &= (1.1\log_{10} f - 0.7)\min(10, h_{\min}) - \\ &-(1.56\log_{10} f - 0.8) + \max\left(0; 20\log_{10}\left(\frac{h_{\min}}{10}\right)\right) \end{aligned} \tag{18}$$

and

$$b = \min\left(0; 20\log_{10}\left(\frac{h_{\max}}{30}\right)\right). \tag{19}$$

Looking at the terms, it is clear that CEPT SE21 model for Tx-Rx distance d shorter than 40 m is the same as the free space propagation model. Equation for L_3, which applies to Tx-Rx distance d longer than 100 m, is a complex equation. For fixed frequency of 400 MHz and antenna heights less than 30 m it reduces to

$$L_3 = 117.36 + 35.22\log_{10} d - a(h_{\min}) - b(h_{\max}). \tag{20}$$

This equation is similar to the FSL model except that the constants are significantly larger. The CEPT SE21 model for separations between 40 m and 100 m is simply linear interpolation between the values of the model at 40 m and 100 m.

4.4 Two-Ray Model

The signal level at the receiver is calculated considering only the contribution of the direct ray and ground reflected ray [8]. The path loss at the receiver is given by

$$L = 20\log\left[\left(\frac{\lambda}{4\pi}\right)\left|\frac{e^{-jkr_1}}{r_1} + \Gamma\frac{e^{-jkr_2}}{r_2}\right|\right], \tag{21}$$

whereat Γ is the Fresnel coefficient of the ground, λ is the wavelength, k is the wave number, and r_1 in r_2 are direct and reflected path lengths, respectively.

The two-ray model is adequate for rural environments with flat ground. But it is also suitable for microcells with low base station antennas where there is a LOS between the transmitter and receiver. In such cases, reflections and diffractions also occur on the walls of the building. These contributions result in rapid variations but do not change the overall path loss of the model.

4.5 Multi-Wall Model

The multi-wall model indicates the path loss as a free space loss together with the losses introduced by walls and floors penetrated by the direct ray between the transmitter and receiver [9]. It was proven that the total floor loss is a non-linear function of the number of penetrated floors. This characteristic is taken into account with an introduction of an empirical factor *b*. The multi-wall path loss is given by

$$L = L_{FS} + L_C + \sum_{i=1}^{I} k_{wi} L_{wi} + k_f^{\left[\frac{k_f+2}{k_f+1} - b\right]} L_f \,, \qquad (22)$$

whereat L_{FS} is the free space loss between transmitter and receiver, L_C is the constant, k_{wi} is the number of penetrated walls of type *i*, k_f is the number of penetrated floors, L_{wi} is the loss of wall type *i*, L_f is the attenuation through adjacent floors and *I* is the number of wall types.

Constant loss factor is a term applied when wall losses are determined on the basis of measurements and is usually close to zero. The third term in previous equation expresses the total wall loss as a sum of the walls between transmitter and receiver. For the practical reasons the number of different walls should be kept low. Otherwise, the difference between the wall types is small and their significance in the model becomes negligible.

It is also important to note that the loss factors are not physical wall losses but model coefficients which are optimized along the measured path. Besides, the loss factors implicitly include the effect of furniture as well as the effects of signal paths guided through corridors.

5 Validation of two-ray and multi-wall propagation channel models for TETRA DMO

Two-ray and multi-wall models have been selected for typical propagation environments such as open flat areas and indoor areas for a fast and straightforward TETRA DMO coverage calculation. The two-ray model has been validated using results of the field measurements using TETRA DMO in an open flat area, while to evaluate accuracy of the multi-wall model applicable for prediction of DMO coverage inside buildings, the measurement campaign was performed inside the premises of our Institute.

The results obtained using the aforementioned models were compared with the measurement results. In order to provide a quantitative measure of the accuracy of the applied empirical models, the absolute mean error (AME) and the root mean squared error (RMSE) were calculated.

The two-ray model simulation results were compared with the measurements taken in a long straight road near Ljubljana. The measurements were performed with two handheld EADS THR 880i terminals and one mobile EADS TMR 880 TETRA terminal, each equipped with an antenna with virtually uniform radiation pattern. The first handheld terminal with the Tx power of 1 W was DMO transmitter, while the other two terminals namely, handheld and mobile, connected to the computer, measured the DMO signal levels. Both received signal levels and Tx-Rx distances were stored into the file. Crosses and circles in Fig. 2 present the values of the measured DMO signal level for handheld and mobile terminal, respectively. The solid curve in Fig. 2 presents the path loss obtained by the two-ray model. It is evident from the results obtained that the measured values are in agreement with the theoretical results. The signal levels decrease with the fourth power of the distance in the far field (distance longer than 10 m) and are almost linear in the near field.

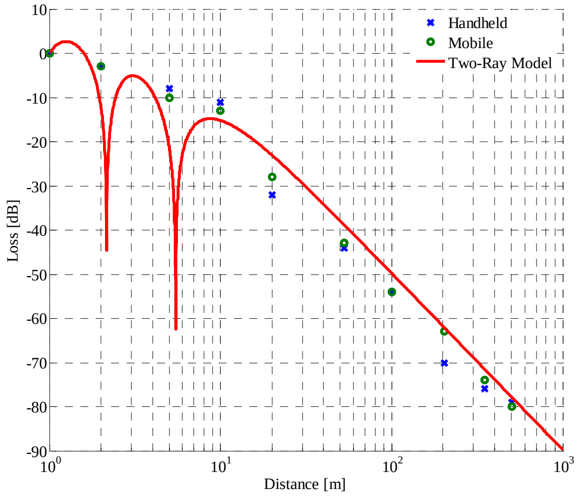

Fig. 2: Two-ray model simulation and measurement results for 'back-to-back' DMO

For an additional verification of previous findings RMSE and AME were calculated. The values of RMSE and AME for handheld terminal are 6.96 dBm and 0.57 dBm, respectively. For the mobile terminal the values are slightly lower – the RMSE is 5.35 dBm while the AME amounts to 0.33 dBm.

The two-ray model simulation results were also compared with the measurement results obtained for the DMO repeater ClearTone CM9000 as a transmitter and the handheld terminal EADS THR 880i as a receiver. In Fig. 3 the values of the measured signal levels and the path loss curve are shown. The measurements were taken only in the far field, because the communication between repeaters and handheld terminals is usually set up only for longer distances.

The measured signal levels in the far field coincide with path loss curve rather well. In this case the signal level in far field also decreases with the fourth power with the distance. The calculated RMSE and AME values, which amount to 5.07 dBm and 0.30 dBm respectively, are comparable with the measurements results for ‘back-to-back’ DMO communication.

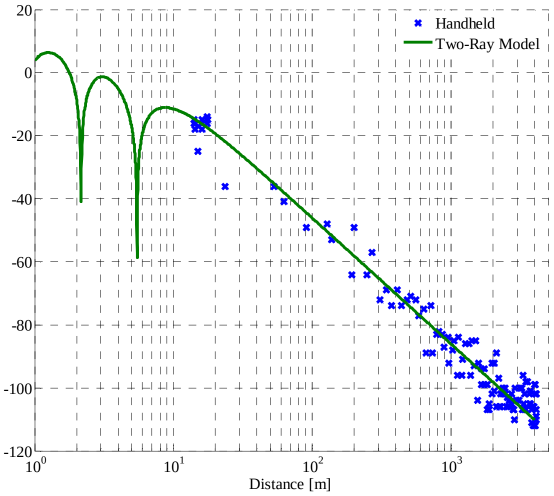

Fig. 3: Two-ray model simulation and measurement results for repeater-DMO

The multi-wall model simulation results were compared with measurements taken in the third floor of a 15.6 m long and 11.5 m wide building at our Institute. Simulation results were calculated by *Radiowave Propagation Simulator* (RPS) program whereat the approximate propagation environment was modelled. The RPS program has a built-in multi-wall path loss model. Parameters for the transmitter and receivers, distributed over the entire floor, were set according to the equipment specifications used in the field measurements. The signal levels, calculated for the entire floor are presented in Fig. 4.

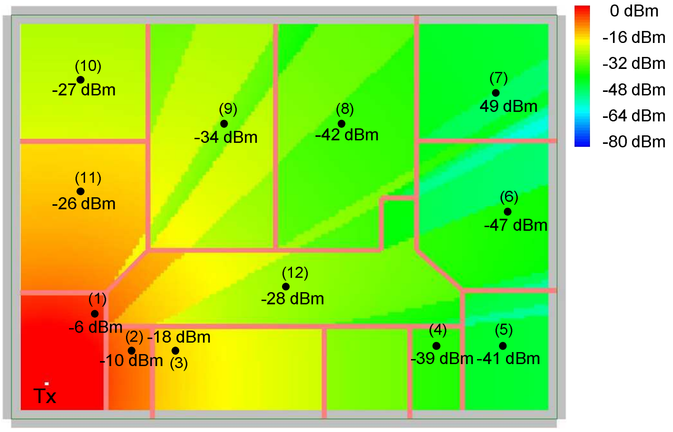

Fig. 4: Multi-wall model simulation and measurement results for ‘back-to-back’ DMO communication

In order to assess the Multi-Wall Model, the signal level measurements were taken in each room of the building. Transmitter and receivers were operating in ‘back-to-back’ DMO mode. The measured signal levels, the location of the transmitter Tx and the measurement locations are shown in Fig. 4.

Analysing the measurement results in Fig. 4, it is obvious that only measurements in points (8) and (11) do not agree well with the simulations. The difference is from 6 to 8 dBm. These two measurements have the main impact on the AME, which is 1.99 dBm while the RMS parameter is relatively low (3.38 dBm). The main underlying reason for the inaccuracy of the received signal strength is inflicted by reflected rays from the tall surrounding buildings. Their contribution to the received signal strength inside the analyzed building can be constructive or destructive. Therefore, it may be concluded that the multi-wall model predicts signal level with sufficient accuracy in the buildings which are not surrounded with high structures. Considering the building structure and the adequate wall and floor attenuation factors, the model can be used for quick and accurate DMO coverage estimation and interference evaluation inside the buildings.

6 Interference Estimation in TETRA DMO by Path Loss Models

One of the most important differences between Direct Mode Operation and the Trunked Mode Operation is in allocation of the uplink and downlink carrier frequencies. While in Trunck Mode Operation uplink and down link operates on different frequencies, the same carrier frequency is used for uplink and downlink in DMO mode. The DMO frequency carrier assignment can be placed anywhere, either within the same band as used for the trunked mode, outside it or between the base stations transmit and receive segments. In most cases the band earmarked for the trunked mode is used. Thus, the direct mode channels can be placed in the same band as the trunked mode base station transmit band or in the same band as the trunked mode base station receive band.

As mentioned, two types of interference exist. When transmitter transmits on its frequency, it creates intermodulation interference on the adjacent transmit frequencies. The second phenomenon is the interference caused by the transmit signal spreading in neighbouring frequency bands. This phenomenon is analysed in subsequent sections.

6.1 Transmitter Interference

Any radio transmitter produces interfering transmission in adjacent frequency bands. If this transmission coincides with the receiver frequency, additional interference at the receiver is produced. For the successful reception the required signal/interference ratio must be maintained. Consequently, when the interference increases, the received signal strength must also be increased to enable communication with required

BER. At the edge of the coverage area the signal is just above the receiver sensitivity. Such an increase in the interference drowns out received signal and the effective range of the communication is reduced.

The TETRA standard specifies maximum levels of transmitter interference that can be produced by the TETRA transmitter, depending on the transmitter class (power) and the frequency offset from its transmission frequency. These levels are expressed relative to the power of the transmitter and are shown in Table 1 [4].

Frequency offset [kHz]	Maximum adjacent power levels [dBc]			
	class 5	class 4	class 3	class 2
25	-55	-55	-60	-60
50 – 100	-70	-70	-70	-70
100 – 250	-75	-75	-78	-80
250 – 500	-80	-80	-83	-85
> 500	-80	-80	-85	-90

Table 1: Maximum adjacent power levels and wideband interference limitation

One approach to quantify the effect of the interference is calculating the reduced effective range of the receiver depending on the location and class of the interferer. From the user perspective the reduction in range is not an immediately noticeable effect. Therefore, more practical calculation is to determine the stay-away distance between receiver and interferer. Basically, this is the minimal required distance between the receiver and interferer which enables an undisturbed reception of the received signal.

6.2 Interference Effects

The BER depends on received signal strength and interference level in the interference limited communication systems. Acceptable level of the interference can be calculated assuming constant received signal strength. Taking into consideration that the interference level decreases with distance between interfere and receiver there exists the receiver-interferer distance where the effect on the receiver is below critical level required for BER. We call this distance stay-away distance.

Pursuant to the given methodology for the stay-away distance calculation [4], the proposed receiver sensitivity value is N_F=-122 dBm and additional loss caused by the body at the receiver and the transmitter is L_A=14 dB. These two assumptions apply only for the handheld terminals. For the mobile terminals with external antenna additional body losses are not taken into account.

In the interference effect calculation it is assumed that the interferer is of power class C and the frequency offset between it and the disturbed receiver is *Δf*. The allowed interference, P_{NR}, can be determined from Table 1. The maximum absolute interference level, P_{NA}, is:

$$P_{NA} = P_c + P_{NR}, \tag{23}$$

whereat the P_C is the power of interferer in dBm. If the value of the previous expression is greater than the receiver sensitivity then the received signal will be affected by the noise. To reduce the interference impact at the receiver, the total path loss needs to be

$$L = P_{NA} - N_F = L_A + L_N \tag{24}$$

Total path loss is made up of a loss incurred due to the separation of the victim receiver and interferer, L_N, and a loss incurred due to other effects, L_A, (antenna gain, body losses, and suchlike). After rearranging equation (24), the path loss is given by:

$$L_N = P_{NA} - N_F - L_A \tag{25}$$

The aforementioned methodology assumes that transmitter is at the maximum permissible range. However, in most cases the transmitter is much closer to the receiver and the signal/interference ratio is much higher than minimal. Therefore, the interference floor uplift can be introduced in the above procedure. The reference threshold defined by the TETRA standard is 19 dB above the receiver sensitivity. Thus, with a N_F=-122 dBm, a signal of -103 dB represents a minimum which may be received. When calculating the effect of interferer interference, the interference floor uplift can simply be added to the noise floor and equation (25) becomes:

$$L_N = P_{NA} - (N_F + N_U) - L_A \tag{26}$$

Conversion of path loss into the physical distance separating the receiver and interferer requires knowledge of the local propagation conditions which enables choosing an appropriate path loss model. The models suitable for the use in the DMO mode and different propagation environments are described in Section 4 and evaluated with simulations and measurement results in Section 5.

Accuracy of the determined stay-away distance strongly depends on the suitability of the model applied for the analysed environment and its accuracy. The model is usually chosen based on the availability of the different parameters, required accuracy, degree of complexity, implementation and calculation complexity.

6.3 Stay-Away Distance and Interference Area

The calculation of minimal stay-away distance incorporates power of the interferer, frequency separation between received and interfering signals and required signal/interference ratio. The influence of the interferer is increasing with an increase in interferer power and decreasing with an increase in frequency separation. The path loss model used in calculation has a significant impact on the accuracy of the results. The path loss model should correspond to the propagation conditions in specific environment. There are at least two methods to estimate stay-away distance, namely the speech quality perceptual method and the interference level calculation method. While in speech quality perceptual method the stay-away distance is determined by subjective perception of the speech quality, i.e. as a function of interference level, the interference level calculation method applies the path loss models to calculate the interference level at the receiver and consequently the stay-away distance. An example of speech quality perceptual method is described in the next subsection, while our research results based on the interference level calculation method are shown in Subsections 6.3.2 and 6.3.3.

6.3.1 Speech Quality Perceptual Method

An example of the speech quality perceptual method for the TETRA DMO is given in [4]. In measurement campaign a class 4 transmitter, a class 5 receiver and interferers were used. The distance between transmitter and receiver varied between 10 and 500 m and the distance between receiver and interferer was measured at the point where user of the receiver perceived that the voice quality of the communication was no longer acceptable. The experiment was performed for frequency separations between the received signal and interferer of 25 kHz, 50 kHz, 75 kHz, 100 kHz, 250 kHz (Fig. 5). The results in Fig. 5 reveal that the stay-away distance is below 3 metres, if the carrier frequency offset of DMO groups are at least 50 MHz., further more stay-away distance is nearly independent on the Tx-Rx distance. However, for the DMO groups using the neighbouring channels, the stay-away distance is substantial and increasing with the Tx-Rx distance.

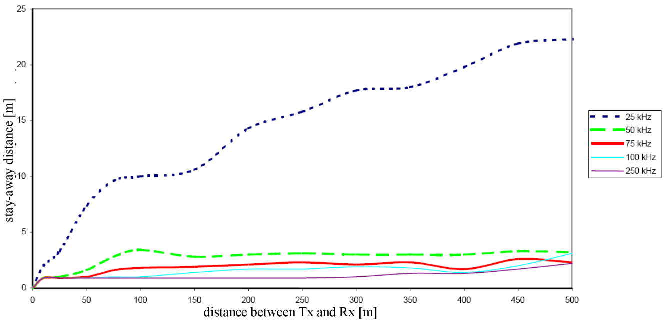

Fig. 5: Measured stay-away distance [4]

6.3.2 Interference Level Calculation Method Assumptions

The methodology of interference level calculation method is explained in Subsection 6.2. The main requirements for the interference calculation are:

- the accurate propagation model for converting path loss into physical distance,
- the known minimal signal/interference ratio for undisturbed communication,
- the known antenna and body losses between transmitter and receiver,
- the linearity of the receiver.

The last requirement cannot be verified directly. Therefore, linear response of the receiver to the interference is presumed.

In the theoretical calculations (Section 6.2) it is assumed that the cumulative body loss comprising both losses namely, between the transmitter – receiver and interferer – receiver is 14 dB. However, based on measurements stated in [4] the body loss between receiver and interferer are 6.6 dB and 9.2 dB between receiver and transmitter. In other words the received signal is attenuated more than interferer which consequence is an increase of the stay-away distance.

According to the standard, the minimal signal/interference ratio which would reduce the quality of the received signal is 19 dB. Measurement result confirms that the margin is set too pessimistically. In [4] the new reduced margin was proposed (8 dB) which significantly decreases stay-away distances.

6.3.3 Stay-Away Distance and Interference Area Evaluation

The class 4 TETRA handheld transmitter and receiver were used to obtain stay-away distance applying the interference level calculation method. Based on the adjacent channel frequency offset and the class of the terminal the values for the maximal permissible power level in adjacent channels were taken from the Table 1. The program package for calculations and graphical representations are written in “Matlab”.

According to the requirements for interference level calculation method explained in Subsection 6.3.2 the path loss calculation model has to be selected for stay-away distances estimation. From the results presented in Section 5, where the two models, namely two-ray path and multi-wall, are validated using path loss obtained from models and measurement results, the two-ray path loss model is selected for open flat areas and multi-wall model for indoor environments.

The signal/interference ratio threshold which still enables undisturbed communication was set to 19 dB in our calculations. No additional losses, for example body loss, were considered.

Highways are very good example of an open flat area where accidents happen frequently. At an emergency scene the number of different rescue teams increases significantly. Therefore, the number of different DMO groups usually operates at the same time and can interfere with each other. To analyse the described situation two-ray model was used for the interference area and stay-away distance calculation.

Fig. 6 shows stay-away distance for the 25 kHz frequency offset. It is evident that the interferer interrupts receiver when the distance between transmitter and receiver exceeds 48 m. Stay-away distance starts increasing linearly at the approximate distance of 100 m while the stay-away distance increases to 125.5 m at 1 km separation between transmitter and receiver. The shape of the curve corresponds to the path loss curve in the linear scale where the curve decreases rapidly to 100 m and is almost linear from 200 m onwards.

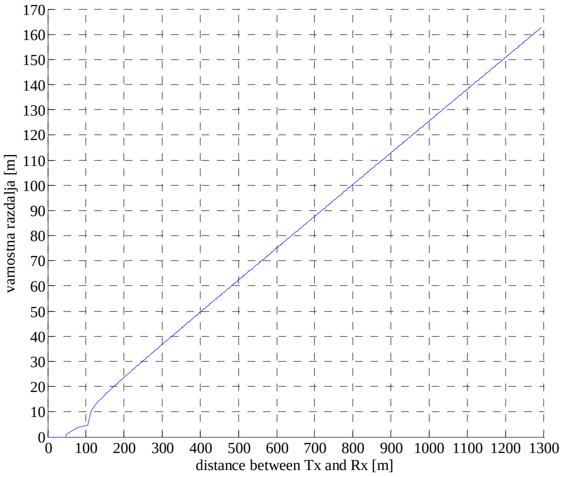

Fig. 6: Stay-away distance, adjacent channel – two-ray model

The interference level of the interferer transmitting on adjacent frequency channel separated by 25 kHz from the carrier frequency of the transmitter is shown in Fig. 7. The receivers are arranged in the mesh of 1100 m x 1100 m with 1 m separation among them. Distance between interferer and transmitter, in Fig. 7 denoted as Txi and Tx, is 1.26 km and is constant.

With the approaching of the receiver to the interferer the interference level increases. The circles in Fig. 7 illustrate the areas where the undisturbed reception of the received signal is prevented. The largest circle has the 181 m radius and corresponds to frequency offset of 25 kHz. The circle bounds the area where normal reception of the received signal is no longer possible. The size of the interference regions for the 50 kHz and 100 kHz offsets are much smaller. For an undisturbed reception receiver must be situated outside the circles with the radius of 70 m and 51 m, respectively.

The calculated stay-away distances are very pessimistic. According to the measurements and simulation results compared in Section 5, it can be assumed that the two-ray model predicts signal strength in open flat areas rather well. Therefore, the main underlying reason for the results inaccuracy is signal/interference margin which is set too high.

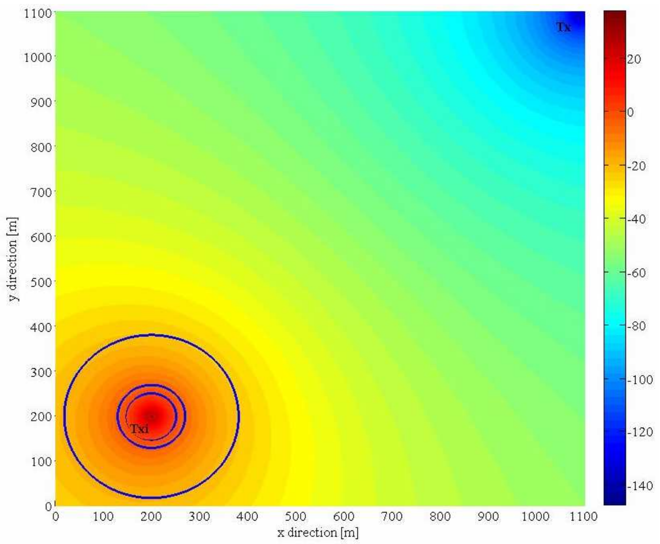

Fig. 7: Signal/interference ratio and interference area of the receiver

Multi-wall model is frequently used for the path loss calculation inside the buildings. The model is described in details in Section 4.5 whereas its accuracy evaluation is performed in Section 5. For the interference area determination and stay-away distance calculation using multi-wall model the RPS program with the analysed environment and built in MWM propagation model was used. For the purposes of graphical representation some results were exported in “Matlab”.

In the simulations the transmitter was placed 1.4 m from the corner of the building. The positions of the interferer were changed along the diagonal toward the opposite corner of the building. The distance between transmitter and interferer thus varied in the range from 0.6 m to 17 m. The receiver was also placed on the same diagonal, i.e. at 15 equidistantly chosen positions. At each receiver position the interfering and the received signal strength and stay-away distances were calculated. The minimum stay-away distance is plotted in Fig. 8 for carrier frequency offset of 25 kHz.

The curve in Fig. 8 is not smooth. The curve peaks and sharp edges coincide with the wall positions. The first smooth part of the room represents the situation when the transmitter, interferer and receiver are in the same room, while in the second smooth part one wall separates the transmitter and the interferer. Consequently, the separation wall decreases the received signal strength significantly which is reflected in the alteration of the stay-away distance slope. The receiver location is still in the same room with the interferer. However, as the distance between the transmitter and interferer is considerable enough, it may happen that the stay-away distance assuming free space loss exceeds room dimensions. As a result, a separation wall arises between the interferer and receiver resulting in a decrease in interfering signal. Consequently, the minimum stay-away distance represented in Fig. 8 falls significantly. It may be concluded that the stay-away distance depends heavily on the number of walls between transmitter-receiver and interferer-receiver, the size of the rooms and on the electromagnetic properties of the walls.

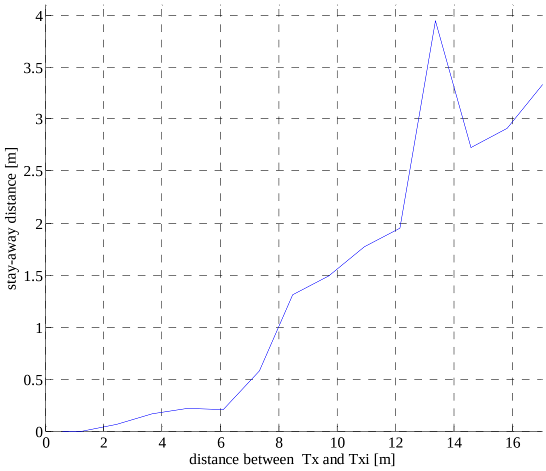

Fig. 8: Stay-away distance, adjacent channel – multi-wall model

Fig. 9a shows the signal/interference ratio and interference area for the interferer operating in adjacent frequency band separated by 25 kHz calculated with the MWM model. The calculation is performed for the third floor of the building appertaining to the Institute. Receivers are placed 1.2 m above the floor and arranged in the mesh with a 0.1 m resolution. The positions of the transmitter and interferer, in Fig. 9 denoted as Tx and Txi respectively, are fixed. In the presented simulation results the said positions are located 15.8 m apart.

It is evident from Fig. 9a that a reduction in the distance between the receiver and interferer causes an increase in the interference. Because the model incorporates additional attenuation of the walls, the size of the rooms and their geometry can also be observed. The area where the reception may be disturbed when the frequency offset equals to 25 kHz is illustrated in Fig. 9b. It includes the whole room with interferer and a part of the neighbouring room. The area of the jammed reception for the frequency offset of the 50 kHz is much smaller and does not extend to the neighbouring rooms – Fig. 9c. In the case of 100 kHz frequency offset between the transmitter and interferer, the reception is interfered only in the close vicinity of the interferer. The

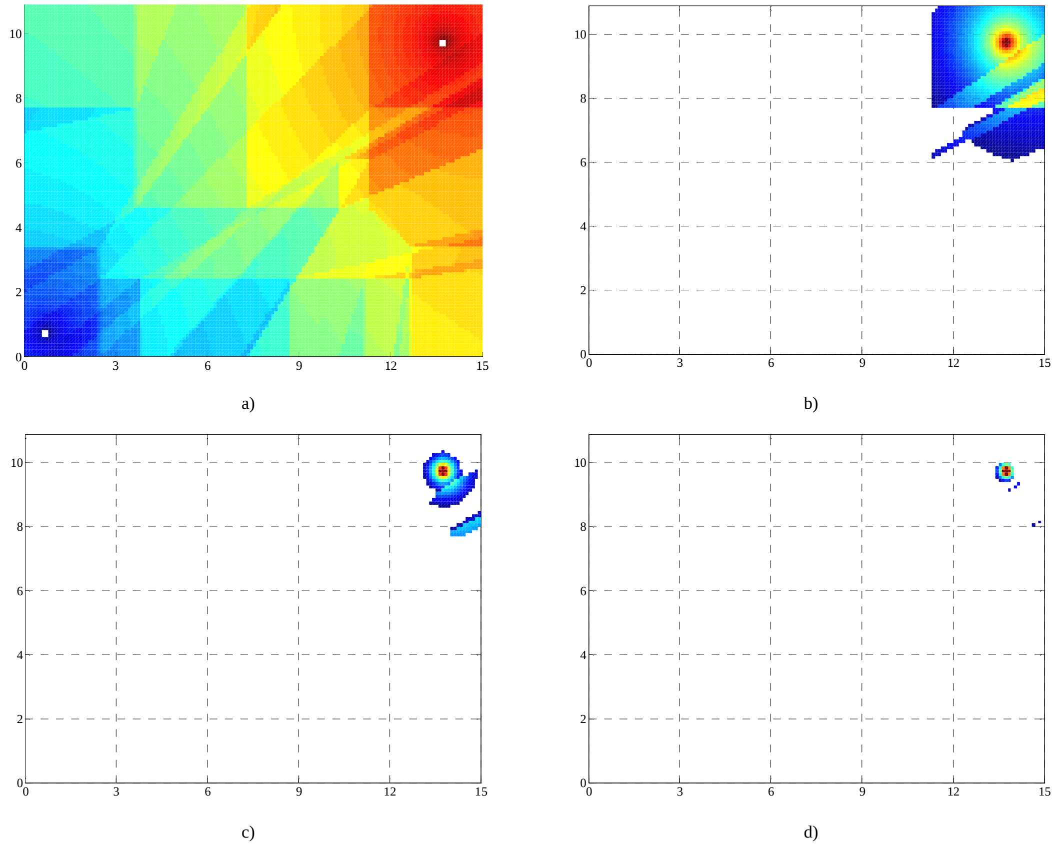

Fig. 9: Signal/interference ratio a) and interference area of the receiver – b), c), d)

interference area for the 100 kHz case is represented in Fig. 9d.

According to the interference result obtained and model evaluation in Section 5 it can be concluded that the MWM model predicts path loss and consequently also the interference area for the buildings which are not surrounded with the high buildings where the additional reflected rays can contribute constructively to received signal strength with the satisfactory accuracy.

7 Conclusion

In the emergency situations the number of the DMO groups and users can be very high, which increases the possibility of interference between them. Therefore, the co-channel interference for the TETRA DMO mode was analysed in this paper.

For the stay-away distance calculation and interference area estimation two-ray path loss model and multi-wall model were used. Both models were evaluated by comparing the field measurements and simulated propagation model results. We can conclude that rough signal coverage prediction for an open area and indoor environment is possible with two-ray path loss model and multi-wall model respectively. In the case of indoor propagation the attenuation regarding to the wall structure, such as a brick wall, plaster wall or concrete wall, has to be measured in advance in order to estimate the signal level inside the buildings with sufficient accuracy.

Results of the interference analyses for typical environments in which the TETRA DMO mode is used have shown that in the presence of a larger number of active DMO groups range of reliable connection is restricted especially by the interference between the users of different groups. Dominant influence of adjacent channel interference is noticeable particularly in environments with high attenuation of the received signal and low interferer attenuation. For instance, if the communication inside the building is established between terminals in different rooms where the separation walls cause high attenuation and the interferer is located in the same room as the receiver, the level of the interference at the receiver is high.

Long roads and railway tunnels are another typical environment, suitable for the TETRA DMO applications. Since no adequate empirical model for radio signal propagation prediction inside the tunnels exists, interference cannot be analysed with the given procedure. Thus, new empirical path loss model based on the field measurements in the 400 MHz frequency band would be helpful.

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