J. King Saud Univ., Vol. 21, *Eng. Sci.* (1), pp. 23-31, Riyadh (2009/1430H.)

TETRA Outdoor Large-scale Received Signal Prediction Model Based on Recent RF Measurements in Riyadh Urban Area

Faihan D. Alotaibi and Adel A. Ali
Electrical Engineering Department, College of Engineering,
King Saud University, P.O. Box 800, Riyadh 11421,
Saudi Arabia
falotaibi@tel.moi.gov.sa
adelali@ksu.edu.sa

(Received 18/11/2006; accepted for publication 14/7/2007)

Keywords: TETRA, Outdoor prediction model, Measurements, Riyadh.

Abstract. TETRA outdoor large-scale received signal prediction model is presented here. The model follows log-distance model. It is derived based on received signal strength survey measurements of a TETRA system, operating in the 300-400 MHz band, in Riyadh City. The model is aimed to assist practicing engineers in the estimation of received power or electric field strength as well as path-loss at any given distance from the base station or vice versa. The model exponent (n) for the selected routes is found to be 3 ± 0.7. However, the overall value of *n* for urban area in Riyadh City is found to be 3.22. It is noted that the values of *n* obtained are low, compared to values obtained in several European cities, as the streets are wider and the buildings' heights are lower in most parts of the routes in Riyadh.

I. Introduction[1]

Received signal prediction models play an important role in the RF coverage optimization and efficient use of the available resources in wireless communication. As the demand for location based services (LBS) increases in the non-line of site (NLOS) environment, a robust received signal prediction model is needed to enhance the accuracy of the LBS techniques that are not based on GPS receivers. This paper presents a large scale received signal prediction model for various types of terrains. The model will be used to develop a mobile station location estimator on a cellular private mobile system which is called Terrestrial Trunked Radio system (TETRA). TETRA was specified by the European Telecommunications Standards Institute (ETSI) as an open standard trunking radio system and is used by public safety and security organizations for services such as emergency services, police, fire fighting as well as utilities services providers. Table 1 contains the main TETRA features and parameters (Dunlop, Girma and Irvine, 1999; Gray, 2003; European Telecommunication Standards, 2004).

Large-scale path loss model for TETRA network implemented in Athens has been presented in (Rittas *et al.*, 2004). The model follows log distance model and the path loss exponent *n*, for the urban environment is found to be in the range $n = 4 \pm 0.5$, whereas the standard deviation σ for small-scale fading fluctuations is equal to $\sigma = 8.6 \pm 0.2$ dB. The model is found for two TETRA base stations only and

(1) Part of this paper was presented in the IEEE Wireless and Microwave Technology Conference, December 4-5, 2006, Clearwater, Florida, USA.

Table 1. The main TETRA features and parameters

System parameters/features	Parameters values/descriptions
Up link frequency bands (MHz)	380-390, 410-420, 450-460
Down link frequency bands (MHz)	390-400, 420-430, 460-470
Digital modulation format	$\pi / 4$ *DQPSK*, 2 bits per symbol
Carrier bandwidth	25 KHz, (25/4 = 6.25 MHz per channel)
Multiple access	TDMA, with 4 channels(time slots) per carrier
Max. data rate	28.8 Kbps (7.2 Kbps per time slot)
Symbol rate/gross bit rate	18 K symbol/sec. or 36 Kbps
Base station power classes	40W (46dBm), 25W (44dBm), 15W (42dBm),10W (40dBm), 6.3W (38dBm),….,0.6W (28dBm) 10 power classes.
Hand-held power classes	3W (35dBm), 1W (30dBm), 0.3W (25dBm).
Hand-held sensitivity for 2% BER.	-103 dBm
Max. vehicle speed	200 kmph
Coverage cell radius	Up to 45 km for open area coverage.

Table 2. The main physical characteristic of the urban areas base stations

Quantity	BS 2	BS 5	BS 9
Base station type	Type 1	Type 1	Type 1
Transmitter's power (W)	39.33	40.1	38
Transmitter's power (dBm)	45.95	46.03	45.80
Cable length (m)	62	30	62
Cable losses (dB)	1.645	0.796	1.645
Antenna gain (dBi) Whip-type / Omni-directional	6	6	6
Antenna height (m)	53	12.5	53
Building height (m)	0	111 (37- story Building)	0
$EIRP_T$ (dBm)	50.305	51.234	50.155

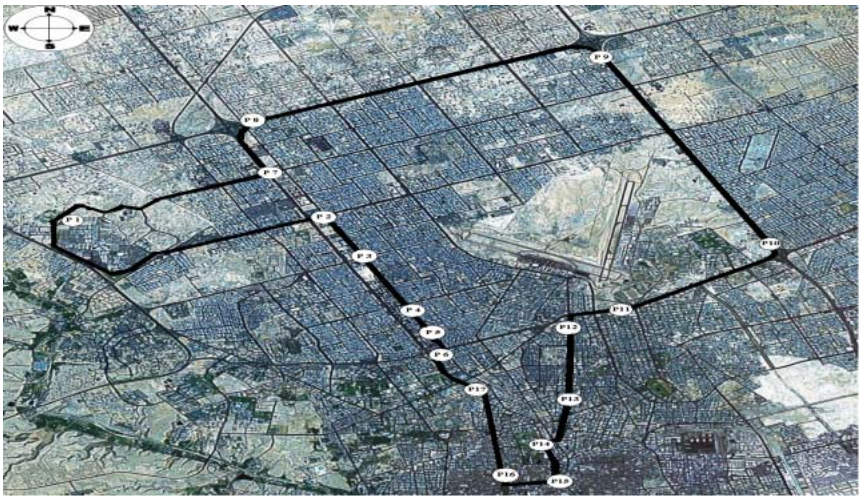


Fig. 1. Copy of part of Riyadh digital map, downloaded from Google Maps website.

is restricted to separation distance above 1 km and less than 5 km. The Root Mean Square Error (RMSE) was not calculated to measure the variation between the median in small-scale window data.

A tuning of "Bertoni-Walfisch" path loss model for GSM-900 MHz Network implemented in Turkey has been presented in (Hanci and Cavdar, 2004). The model is based on measurements for several areas in Istanbul. The path loss exponents n for these areas were found in the range from 2 to 4.4. Statistical analysis parameters such as Cumulative Fade Distribution (CFD), Average Fade Duration (AFD), and Level Crossing Rate (LCR) have been calculated. However, RMSE values are quite large.

A comparison of different prediction methods with the observed path losses have been presented in (Rama Rao *et al.*, 2000) for VHF and UHF bands. The comparison showed that Hata's prediction method gave better agreement in all targeted areas. This is due to the fact that Hata incorporates correction factors for various environments. COST 231 Walfisch–Ikegami method is in agreement in urban and suburban areas in VHF band. The path loss exponents obtained (Rama Rao *et al.*, 2000) for urban, suburban and open areas are 3.3, 2.5 and 2.2 respectively. The standard deviations of observed path loss values in urban and suburban areas at 200 MHz are 3.4 and 4.6 dB respectively, and the standard deviations of the observed path loss values in suburban and open areas at 400 MHz are 6.0 and 7.7 dB respectively.

It has been observed that the prediction model's parameters obtained here achieved better prediction compared to the models' parameters available in (Rittas *et al.*, 2004; Hanci and Cavdar, 2004; Rama Rao *et al.*, 2000). This can be observed from the smaller values of RMSE achieved using the obtained models parameters. We attribute that to the difference between Middle East environments, due to its geographical conditions, and the various propagation terrains available in the literature in other places. This paper is organized as follows. In Section II, Field measurements procedure and locations are discussed. Section III presents hardware and software tools that have been used. Received signal prediction model and statistical analysis are presented in section IV. In Section V, measurement analysis, results and discussions are given. Conclusions are summarized in Section VI.

II. Field Measurements

TETRA survey propagation measurements have been conducted for the existing Saudi Arabian National Guard (SANG) TETRA system in Riyadh City. The system consists of several base stations covering the whole of Riyadh city. Base stations number 2, 5 and 9 cover urban areas, whereas the other base stations cover suburban areas. The main physical characteristics of the urban areas base stations are listed in Table 2. The selected part of Riyadh City for the survey measurements is shown in the digital map copy of Fig. 1.

Measurement route is determined based on radio signal coverage and other propagation parameters conditions. These are: a) The route should go through metropolitan areas as long as it can; b) the route must pass through the suburban area as well as open areas; c) it must also pass through different types of terrains. This route is marked with dark black color line on the city map. On this route, 17 outdoor fixed points have been selected and labeled with numbers enclosed in small white circled boxes. Military and commercial GPS based on the World Geodetic System 1984 (WGS 84) have been used to determine the coordinates of these points.

Recording of the measurements was started on 4th December 2005, and was completed by 3rd January 2006. To increase the reliability, each measurement was carried out twice a day (morning and evening). Measurements were carried out using Motorola Scout software. Different radio coverage conditions outdoor has been also considered. The effect of mobility in different radio coverage conditions has been investigated as well. The General Directorate of Military Survey (GDoMS) also participated in these measurements by providing accurate estimations of the locations of 17 fixed points distributed along the selected route, in addition to the TETRA network base stations locations. These points have been selected in known main roads intersections and they have been used for small-scale fading fluctuations analysis.

While traversing the selected route, the recording of the measurements at the 17 fixed points were made in standstill condition, while the measurements between fixed points were made in moving condition at an approximate speed of 40 km/h. For high density urban area, measurements were recorded on the move. This enabled us to study the propagation behavior of TETRA radios under different outdoor propagation conditions, i.e. urban (metropolitan), suburban, rural (open) areas with different vehicular speeds. Moreover, the effect of the small-scale fading was also investigated. This has been done by recording data every second with TETRA hand-held radio which was mounted in a survey vehicle at a height of 1.5 m above the ground level. Enormous amount of data was collected while performing the measurements.

III. Measurements Tools: Hardware and Software

a) Military survey equipments

As mentioned previously, the General Directorate of Military Survey participated in these measurements. Their staff used the Trimble GPS Total Station 5700 system. This system is based on a control surveying principle. It is used to determine the coordinates of selected reference marks in a certain geographic location. The station is integrated with GPS, radios, survey controller, and office software in order to achieve the most accurate coordinates. The Trimble system (fast static type) yields baseline components that are precise to be better than 1 cm ± 1 ppm. From these measurements, it has been found that the difference between the coordinate's located using Trimble system and the commercial GPS is in the range of ± 10-25 m. More technical details about Trimble system can be found in (Trimble Company website, 2006).

b) TETRA signal propagation survey equipments

The equipments and the tools that have been used to conduct these measurements are listed below:

1. IBM compatible laptop.
2. MTP 700 Motorola TETRA hand-held radio (TETRA Mobile Station "MS").
3. Programming stand PMLN4510.
4. Programming cable FLN9636.
5. Garmin 176C GPS.
6. Attached GPS antenna.
7. External GPS antenna.
8. Motorola Scout software version 5.6.1 for TETRA network measurements.

The propagation survey equipments were connected. Motorola TETRA hand-held radio and GPS were connected to the laptop. GPS receiver was programmed on NMEA Mode, whereas MTP700 radio has been programmed on Air Tracer Mode. The measurements emphasized on recording where: a) Latitude, longitude and altitude of the TETRA MS radio, b) vehicular speed, and c) Receive Signal Strength Indicator (RSSI) for serving base station and the strongest three foreground stations in dBm.

IV. Received Signal Prediction Model and Statistical analysis

a) Received signal prediction model

Based on the above mentioned findings, the received signal prediction model has been constructed in the metropolitan area of Riyadh City. Generally, the log-distance propagation model was used to estimate path loss model parameters from the measured data. The large-scale path loss model $PL(d)$ in *decibel* for an arbitrary T-R separation (*d*) is expressed as follows (Rittas *et al.*, 2004; Hanci and Cavdar, 2004; Constantino and Zamanillo, 2002):

$$PL(d) = A\log(d) + C \qquad (1)$$

where A is the slope of the path loss curve in dB/decade, and C is the path loss at reference point. Equation (1) can be written in the known following form:

$$PL(d) = 10.n.\log\left(\frac{d}{d_o}\right) + PL(d_o) \qquad (2)$$

where n is the path loss exponent, and $PL(d_o)$ is the reference path loss at distance d_o. Now, the predicted signal $PD(d)$ can be obtained as:

$$PD(d) = EIRP_T - PL(d) \qquad (3)$$

and $EIRP_T = P_T - L_C + G_T \qquad (4)$

where $EIRP_T$ is the effective isotropic radiated power of the TETRA base station, P_T is the base station transfer output power, L_C is antenna cable loss, and G_T is transmitting antenna gain. These powers, loss, and gain are added in dBm. Therefore, from Eqs. (1) and (3), $PD(d)$ can be obtained as follows:

$$PD(d) = -A\log(d) + C_1 = -10.n.\log(d \cdot \frac{d_o}{d_o}) + C_1 \qquad (5)$$

where $C_1 = EIRP_T - C$. Similarly as in Eq. (2), the large-scale received signal prediction model $PD(d)$ in *decibel* for an arbitrary T-R separation (d) can be expressed as follows:

$$PD(d) = PD(d_o) - 10.n.\log\left(\frac{d}{d_o}\right) \quad (6)$$

where $PD(d_o)$ is the reference predicted signal at distance d_o and it is written as:

$$PD(d_o) = C_1 - 10.n.\log(d_o) \quad (7)$$

b) Statistical analysis

1. The model's goodness of fit statistics

In order to examine the goodness of logarithmic fit, the root mean squared error (RMSE) and the coefficient of determination (R^2) have been calculated. These two statistical parameters are defined as:

i) RMSE: This statistic gives a quantitative measure on how close (on the average) are the RSSI predicted values, which are estimated using the fitting model, to the measured RSSI values. RMSE value closer to 0 indicates a better fit. The following equation defines RMSE:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{m}(y_i - \hat{y}_i)^2}{m}} \quad (8)$$

where m is the raw length of measured data matrix, y_i is the measured RSSI, and $\hat{y}$ is the predicted RSSI.

ii) Coefficient of determination $\left(R^2\right)$: This statistic measures how successful the fit is in explaining the variation of the data. It is defined as the square of the correlation between the measured RSSI values and RSSI predicted values. R^2 always takes values between 0 and 1. As R^2 reaches 1, the regression points tend to align more accurately along the model curve. Mathematically it is defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{m}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{m}(y_i - \bar{y}_i)^2} \quad (9)$$

where $\bar{y}$ is the mean of the measured RSSI.

2. Channel fading characteristic

There are two different types of fading: the small scale and the large scale fading. To test the measured RSSI values fluctuations (variations), variance (*VAR*) and standard deviation have been recommended. The *variance* (*VAR*) and the *standard deviation* (σ) are defined as:

$$VAR = \sigma^2 = \frac{m.\sum_{i=1}^{m}(y_i)^2 - \left(\sum_{i=1}^{m} y_i\right)^2}{m(m-1)} \quad (10)$$

Small scale fading is defined as the fluctuations of the measured RSSI values (black spots in Fig. 2) around the window median RSSI value, which is calculated for the predefined interval of 40 wave length (λ). Its standard deviation distribution, for the same separation distance from base station, is considered to be Gaussian (normal) independently of their direction (azimuth) from base station, whereas the large scale fading is described by the variation of the window median RSSI value with respect to the distance. The total fading is defined as the variation of the measured data.

Small scale fading standard deviation (σ_S), the large scale fading standard deviation (σ_L) as well as total fading standard deviation (σ_{TM}) of the measured RSSI have been obtained. The total standard deviation can be alternatively calculated as the combination of the standard deviation of the independent small and large fading normal distributions. This mathematical total standard deviation (σ_{TE}) is given by the following equation (Rittas *et al.*, 2004):

$$\sigma_{TE} = \sqrt{\sigma_S^2 + \sigma_L^2} \quad (11)$$

V. Measurement Analysis: Results and Discussions

In this section, we present the measurement analysis based on the data collected from base stations 2, 5 and 9 with omni-directional antennas, for the selected route passing through the urban area of Riyadh City. The selected route was divided into four sub-parts; (i) Olaya Main Street, (ii) Khurais Road, (iii) King Abdulaziz & Prince Faisal Roads, and (iv) King Fahd Road. The details of these parts are given in Table 1. The data collected while traversing these routes from the above mentioned base stations are presented in Fig. 2 (a)-(e). Figure 2 (a), (b), (c) and (d) present the RSSI data collected for the sub-parts, whereas Fig. 2 (e) presents the RSSI data collected for the all parts.

The x-axis presents the distance between the base stations and the mobile station (TETRA hand held radio). This distance is calculated from the coordinates obtained from the commercial GPS, for the mobile station and the base stations locations, whereas the y-axis presents the corresponding RSSI (from the above three base stations) at that distance. Curve (1) is a logarithmic fit to the window median RSSI values. The median of the measured RSSI of the small-scale window is obtained at every 40 λ intervals using a sliding window of 80 λ. Curve (2) passes through these window median values. The measured data having T-R distances less than or equal to 9 km has been considered, since 9 km radius corresponds to a cell-edge (in the urban area) where the received power has fallen close to the dynamic sensitivity level of a TETRA receiver (set at -103 dBm, according to the ETSI standards (European Telecommunication Standards, 2004)). Also, the targeted area is located within 9 km from all base stations. This distance is almost twice the distance that has been obtained in (Gray, 2003).

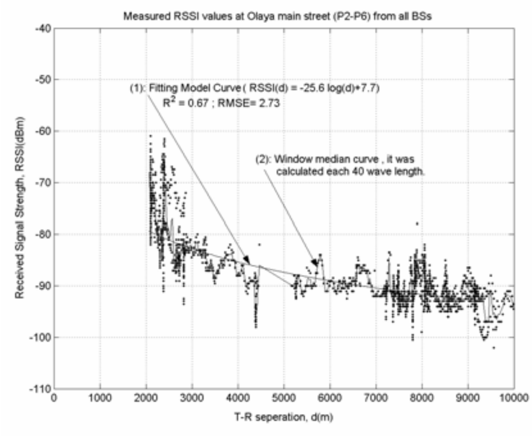
The near zone of propagated measured signal is found in the range of 1 km from the base station. In this zone, the RSSI does not comply with the log distance model, thus limiting the data fitting of the RSSI measurements in the range of 1-9 km.

Using the aforementioned expressions (Section IV), the details of the model parameters (n, and C_1) with 95% confidence interval and the statistical analysis for the sub-routes as well as the overall route are presented in Table 4. From Table 4, we can say that the predicted model, Eq. (5), fits well with the measured data for the high density urban areas routes (King Abdulaziz & Prince Faisal Roads) than urban areas routes (Olaya Street and Khurais Road). In spite of Olaya Street passing through the highest towers in the city, the value of n is low compared with the other roads that pass through the urban areas. This has been found to be due to two reasons. Firstly, Olaya Street has open areas in certain sections. Secondly, the nearest TETRA base station is located at 2 km from this street, and we found that the decay of the received signal strength in the 1-2 km is, in general, higher than in longer distances. Thus, with no data present in 1-2 km at this street (Fig. 2 (a)) reduces the value of its n. The value of n for the overall selected route is found to be 3.22 with the best fitting. This exponent is low compared to the European cities, as the streets are wider and the buildings' heights are lower in most parts of the route. This result enhances the hypothesis that states, "Each environment has its effects on the wireless communications propagation".

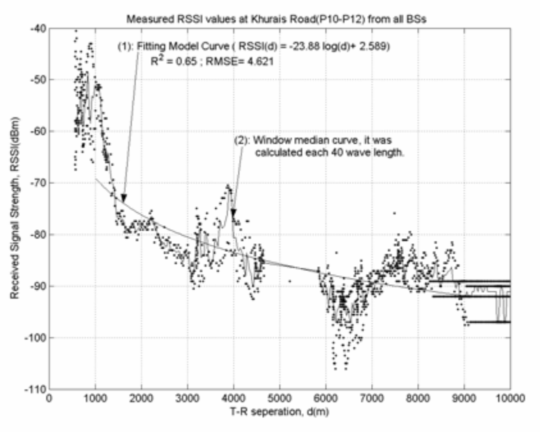
VI. Conclusion

The paper concludes that TETRA outdoor large-scale received signal prediction model follows log-distance model. In Riyadh City, the model exponent (n) is equal to 3 ± 0.7. The average value of the standard deviation for small-scale fading fluctuations over a short period of travel distance 40 λ is found to be in the range of 2.5-4.7. In this study, the antenna height, heights of the nearby buildings and terrain profile have not been considered. The impact of these correction factors to the log-distance prediction model may increase the accuracy of prediction. Log-distance prediction model by itself has its limitation when used in high density urban areas, as the correction factors are dominant in such environments. The effect of these factors shall be considered in our future work.

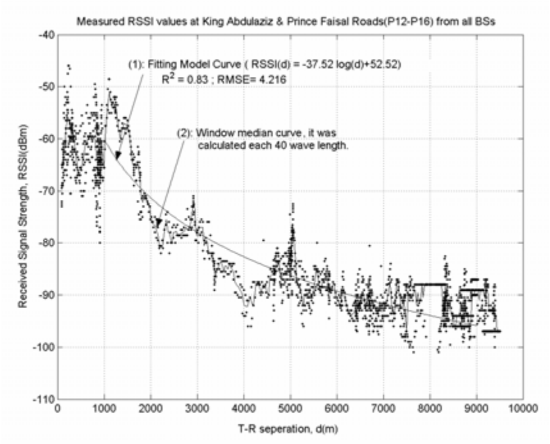
Acknowledgments. The authors wish to thank the following agencies, companies and individuals who either participated or supported the propagation survey and data acquisition: SANG, GDoMS entities, Motorola, and Nasco companies, Cap. M. Al-Sultan from SANG, Mr. S. Al-Shehree and Mr. K. Al-Otaibi



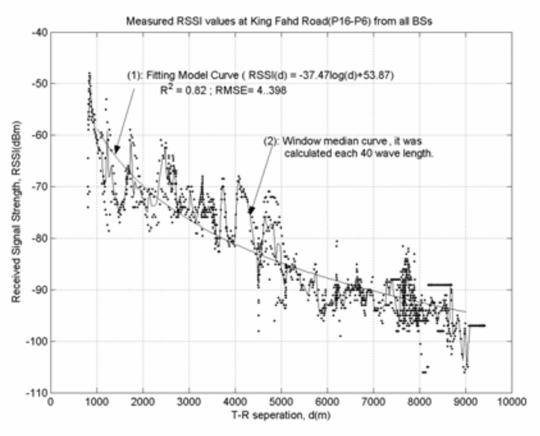
(a)



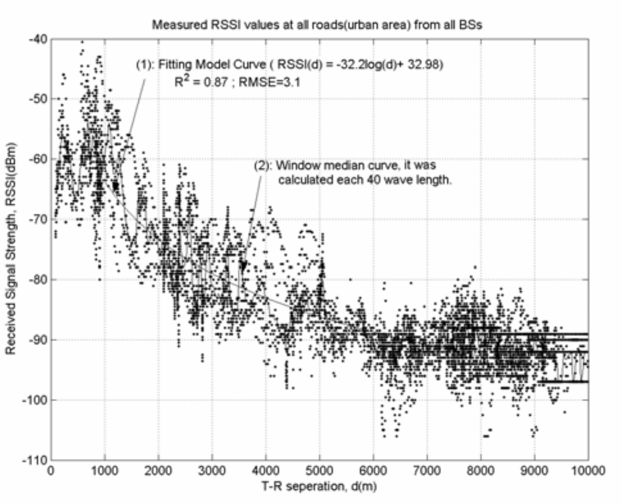
(b)



(c)



(d)



(e)

Fig. 2. (a), (b), (c) and (d) show the data collected for the sub-routes parts, whereas (e) epicts the data collected for the overall sub-routes.

Table 3. Details of the selected route parts

Sub-parts/ Between Points	Name and Description	Ave. Street Width	Street/Road length	Average Building Height	No. of collected data points
2-6	Olaya Main Street	60m	7km	25m	1743
10-12	Khurais Road	50m	8km	20m	1046
12-16	King Abdulaziz and Prince Faisal Roads. (Riyadh down town)	40m	8km	20m	1934
16-6	Part of King Fahd Road	80m	7km	20m	1091
	All the above parts	58m	30km	22m	5814

Table 4. Details of model parameters with the statistical analysis

Sub-parts Between points	Description	n	C_1	$RMSE$	R^2	σ_S	σ_L	σ_{TE}	σ_{TM}
2 –6	Olaya Street	2.56	7.7	2.73	0.67	2.5	4.88	5.48	7.46
10-12	Khurais Road	2.388	2.589	4.621	0.65	3.51	10.27	10.85	8.81
12-16	King Abdulaziz and Prince Faisal Roads	3.752	52.52	4.216	0.83	2.722	11.74	12.10	8.952
16-6	King Fahd Road	3.747	53.87	4.398	0.82	3.24	11.24	11.7	10.10
All the above	Part of the selected route	3.22	32.98	3.1	0.87	4.71	10.93	11.90	8.82

from GDoMS, and Mr. Abdel Nasser Abu Zaid from Motorola. Special thanks go to Dr. Saud Al-Semari for his support throughout. The authors also acknowledge the two anonymous referees for their valuable comments during the review process.

References

Constantino, P.V. and Zamanillo, J.M. "Path-loss Model for Broadcasting Applications and Outdoor Communication Systems in VHF and UHF Bands." *IEEE Trans. on Broadcasting*, Vol. 48, No. (2), (2002), 91-96.

Dunlop, J.; Girma, D. and Irvine, J. *Digital Mobile Communications and the TETRA System*. England: John Wiley & Sons, (1999), 200 p.

European Telecommunication Standards. "ETSI EN 300 392-2: Terrestrial Trunked Radio (TETRA); Voice Plus Data (V+D) - Part 2: Air Interface (AI)." V2.4.2, (2004), 50-96.

Gray, D. *TETRA: The Advocate's Handbook, TETRA Advocate*. England: TETRA Advocate, (2003).

Hanci, Y.B. and Cavdar, I.H. "Mobile Radio Propagation Measurements and Tuning the Path Loss Model in Urban Areas at GSM-900 Band in Istanbul, Turkey." *IEEE Vehicular Technology Conference (VTC2004),* Vol. 1, (2004), 139–143.

Rama Rao, T.; Bhaskara Rao, S.V.; Prasad, M.V.S.N.; Sain, M.; Iqbal, A. And Lakshmi, D.R. "Mobile Radio Propagation Path Loss Studies at VHF/UHF Bands in Southern India." *IEEE Trans. on Broadcasting*, Vol. 46, No. 2, (2000), 158-164.

Rittas, N.E.; Asimakopoulos, A.G.; Constantinou, P.; Polydoros, P.I. and Xenikos, D.G. "Path Loss Model for TETRA Networks in Metropolitan Areas." *Proceeding of ISCC2004*, Vol. 2, (2004), 690-695.

Trimble Company website. (http://www.trimble.com/locator).

نموذج المقياس الكبير لتوقع الإشارة اللاسلكية الخارجية لنظام تيترا بناءً على قياسات ترددات راديو حديثة في المنطقة الحضرية بمدينة الرياض

فيحان بن دعيج العتيبي، وعادل أحمد علي

قسم الهندسة الكهربائية ، كلية الهندسة ، جامعة الملك سعود ،

ص.ب. ٨٠٠ ، الرياض ١١٤٢١ ، المملكة العربية السعودية

falotaibi@tel.moi.gov.sa
adelali@ksu.edu.sa

(قدم للنشر في١٨/ ١١/ ٢٠٠٦م؛ وقبل للنشر في ١٤/ ٠٧/ ٢٠٠٧م)

الكلمات المفتاحية: نظام تيترا، نموذج توقع فقد لاسلكي خارجي، قياسات، الرياض.

ملخص البحث. يُقدم هذا البحث نموذج المِقياس الكبير لتوقع الإشارة اللاسلكية الخارجية لنظام تيترا. يتبع النموذج لوغاريتم المسافة. تم بناء النموذج باستخدام قياسات حديثة للإشارات اللاسلكية لنظام تيترا يعمل بمدينة الرياض في النطاق الترددي ٣٠٠ -٤٠٠ ميجاهيرتز. يهدف النموذج إلى مساعدة المهندسين التطبيقيين في تقدير الطاقة المستلمة أو شدة المجال الكهربائي، وكذلك حساب الفقد عند أي مسافة من المحطة القاعدية أو العكس. وجد أن المعامل (n) للنموذج في الطرق التي تم سلوكها لقياس الإشارات اللاسلكية يتراوح بين ٠,٧ ± ٣. لكن، قيمة نفس المعامل لمجمل الطرق في المنطقة الحضرية بمدينة الرياض وجد أنه ٣,٢٢ .جدير بالذكر أن قيم المعامل (n) المستخرجة هنا أقل مقارنة مع القيم لنفس المعامل المستخرجة في بعض المدن الأوروبية ويرجع السبب لسعة الشوارع وانخفاض المباني نسبيًّا في معظم طرق مدينة الرياض.