applied sciences

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Radio Planning Considerations in TETRA to LTE Migration for PPDR Systems: A Radioelectric Coverage Case Study

Diego del Rey Carrión [1], Leandro Juan-Llácer [2,*] and José-Víctor Rodríguez [2]

1 Dirección General de Seguridad Ciudadana y Emergencias, Consejería de Presidencia y Fomento—Región de Murcia, 30100 Murcia, Spain; diego.delrey@carm.es

2 Universidad Politécnica de Cartagena, 30202 Cartagena, Spain; jvictor.rodriguez@upct.es

* Correspondence: leandro.juan@upct.es; Tel.: +34-968-325-954

Received: 28 November 2018; Accepted: 25 December 2018; Published: 11 January 2019

Abstract: Transitioning a Terrestrial Trunked Radio (TETRA) network to a Long-Term Evolution (LTE) network in public protection and disaster relief (PPDR) systems is a path to providing future services requiring high radio interface throughput and allowing broadband PPDR (BB-PPDR) radio communications. Users of TETRA networks are currently considering how to deploy a BB-PPDR network in the coming years. This study offers several radio planning considerations in TETRA to LTE migration for such networks. The conclusions are obtained from a case study in which both measurements and radioelectric coverage simulations were carried out for the real scenario of the Murcia Region, Spain, for both TETRA and LTE systems. The proposed considerations can help PPDR agencies efficiently estimate the cost of converting a TETRA network to an LTE network. Uniquely in this study, the total area is divided into geographical areas of interest that are defined as administrative divisions (region, municipal areas, etc.). The analysis was carried out using a radio planning tool based on a geographic information system and the measurements have been used to tune the propagation models. According to the real scenario considered, the number of sites needed in the LTE network—for a specific quality of service (90% for the whole region and 85% for municipal areas)—is a factor of 2.4 higher than for TETRA network.

Keywords: radio planning; TETRA; LTE; geographical information systems (GIS)

1. Introduction

The conversion of a Terrestrial Trunked Radio (TETRA) network to a Long Term Evolution (LTE) network in public protection and disaster relief (PPDR) systems is a possible solution to provide future services requiring high radio interface throughput and allowing broadband PPDR (BB-PPDR) radio communications [1]. In Report 218, The Electronic Communication Committee (ECC) proposed a roadmap until 2025 for the transition to broadband communication in PPDR systems [2]. This roadmap envisages coexisting TETRA and LTE networks for several years until the LTE system has all the functionalities of the PPDR systems. Therefore, the introduction of LTE for PPDR should complement, not replace, existing TETRA networks, which will continue to be the best choice for short-term mission-critical voice service.

In addition, PPDR users cannot leave their current TETRA systems until a new mobile broadband network is built that is able to provide radioelectric coverage equal to or better than the radioelectric coverage currently provided by TETRA systems. Therefore, before any broadband solution can replace the current TETRA systems, the LTE network should meet all radioelectric coverage requirements currently satisfied by the existing network.

The most plausible future scenarios to deliver the increasingly data-intensive applications demanded by PPDR agencies are expected to rely on the use of both dedicated and commercial LTE networks [3]. For rural areas, the base stations of a radio communication system are located in the mountains, and the radioelectric coverage has 'dark zones' (without radioelectric coverage), usually in forests, mountains, rivers, etc. In these zones, operators are not interested in deploying new base stations to offer broadband communications. However, in urban environments, operators have already deployed commercial broadband networks, that could be used by PPDR agencies for broadband communications. Therefore, the possibility of a hybrid model (dedicated network for rural areas and commercial networks for urban areas) could be an interesting solution for BB-PPDR radio communications.

More than 114 countries around the world have deployed TETRA networks (at the regional or national level) in the past years according to The Critical Communications Association (TCCA) [4]. Now, the users of these networks are considering how to proceed to achieve a BB-PPDR network in the coming years. Therefore, PPDR agencies are interested in analyses of the many issues (cost analysis of the resources needed, the expected radioelectric coverage, quality of service, etc.) involved in planning the transition of a TETRA network to an LTE network.

A framework for the modeling and planning of an LTE public safety broadband network has been presented by Rouil et al. [5]. The study was carried out on a nationwide scale, dividing the total area into 20 × 20 km squares and establishing a minimum percentage of radioelectric coverage in each square.

In this study, several radio planning considerations in the TETRA to LTE migration for PPDR networks are offered. In this case, different from Rouil et al.'s work [5], the total area is divided into geographical areas of interest that are defined as administrative divisions (region, municipal areas, natural parks, etc.). To illustrate this proposal, a radioelectric coverage analysis in a rural area with an existing TETRA network that has to transition to an LTE system has been carried out in a real scenario by means of both simulations and measurements. The analysis was performed by taking advantage of the potential of a radio planning tool [6] based on a geographic information system (GIS) [7], and the measurements were performed and used to tune propagation models. The proposed methodology can help PPDR agencies efficiently estimate the cost of transitioning a TETRA network to an LTE network.

2. Radio Planning Aspects

2.1. Scenario

RADIECARM is the TETRA network deployed by the Regional Government of Murcia (Spain) that is used by the emergency and safety services (fire brigade, police, forest police, etc.). All these services are coordinated by the Emergency Coordination Center 112. RADIECARM is a dedicated network with 16 base stations located in mountains and around 2000 terminals. In Figure 1, we can see the typical infrastructure (tower, equipment, etc.) at a site and, in Figure 2, a mobile terminal mounted in a four-wheel drive vehicle. Figure 3 shows the 16 TETRA base stations (red circles).

(**a**) (**b**)

Figure 1. (**a**) Telecommunication tower with antennas and stand and (**b**) TETRA base station equipment.

Figure 2. (**a**) Four-wheel drive vehicle with the TETRA antenna and (**b**) TETRA Mobile station equipment.

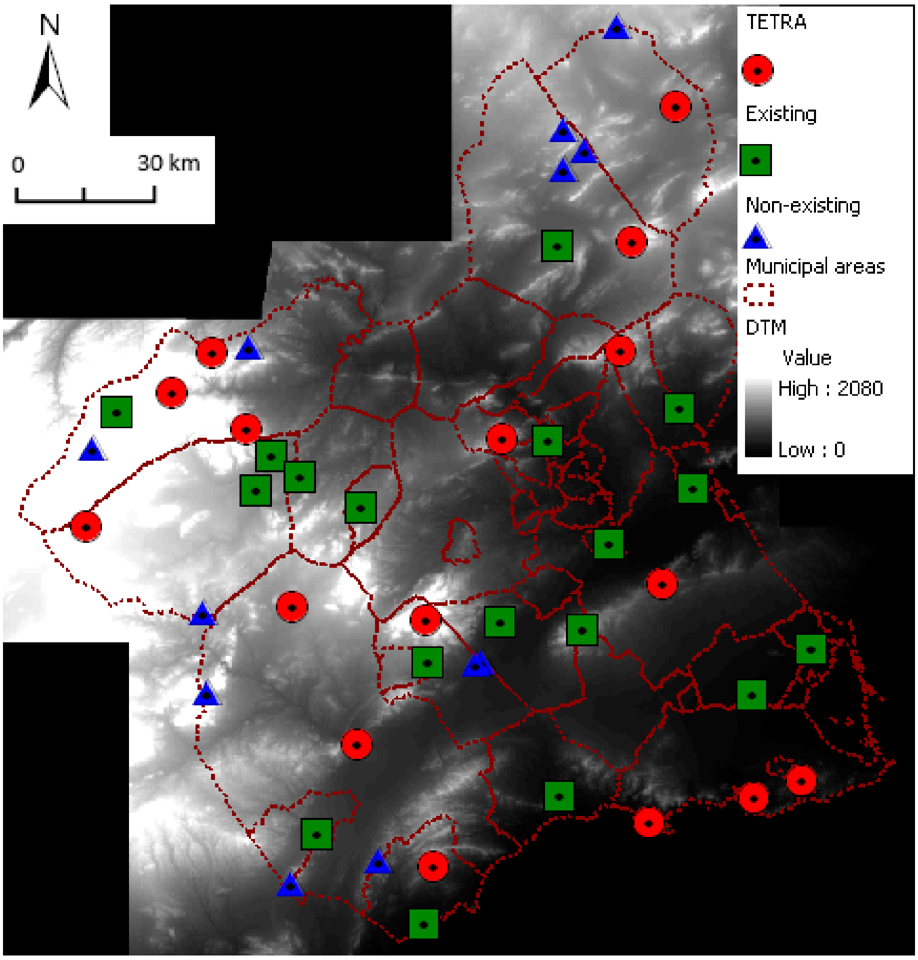


Figure 3. Digital terrain model (raster), sites (vector points) and municipal areas (vector polygons).

2.2. Radio Planning Tool

To carry out the radioelectric coverage analysis, the application RADIOGIS [6], which is a tool developed by the authors for the management and calculation of the radioelectric coverage of radio communication systems such as GSM, UMTS, LTE, TETRA, TDT, WiFi, etc., was used. RADIOGIS works on Windows PCs and is integrated with the GIS software ArcGIS 9.1 from ESRI. RADIOGIS has, among others, the following functionalities:

a) Calculations of power, electric field, or power density radioelectric coverage while being able to select the propagation model to be applied: ITUR-526 [8] and ITUR-1546 [9] for rural environments; Okumura-Hata [10], COST-231 [11] and Walfisch-Bertoni [12] for urban areas.
b) Percentage threshold calculations using a vector layer containing municipal areas, roads, etc.
c) Management of databases of sites, power density radioelectric coverage, power systems, measurement campaigns, etc.

2.3. Frequency Bands

For the existing TETRA network, the frequency band for RADIECARM is 380–385 MHz (uplink, UL) and 390–395 (downlink, DL), which is the band reserved for PPDR systems in Europe [13].

For the new LTE network, several possibilities are available for the frequency band. ECC Report 218 [2] develops the necessary conditions to create a harmonized European framework for the implementation of future BB-PPDR systems. This report proposes the concept of 'flexible harmonization' to enable an efficient implementation of BB-PPDR systems. The frequency bands identified as candidates for harmonization are:

- 400 MHz (410–430 MHz and 450–470 MHz)
- 700 MHz (694–790 MHz)

In our analysis, the frequency bands 699–716 MHz (UL) and 729–746 MHz (DL) were used. These frequency bands meet spectrum regulations for public safety users and broadband services laid out in Spain's National Table of Frequency Allocations. Moreover, they are E-UTRA operating bands according to the ETSI [14,15].

2.4. Digital Information

The Murcia Region (South-West of Spain) is 11,296 km^2. The territory is organized into 45 municipalities, and each municipality delimits an area (municipal area) (see Figure 3). The geographical information has been obtained from the National Geographical Institute of Spain. A digital terrain model (DTM)—in a raster format [7]—with a 100 × 100 m cell size (see Figure 3)—was used for the radioelectric coverage calculations in rural environments, which represents a compromise between accuracy and computation time. We can also observe the municipal areas as a vector layer with an associated attribute table that contains information (name, extension, population, etc.) in Figure 3 [7].

2.5. Quality of Service (QoS)

The signal received in mobile communication presents wide random variations that can be modeled by introducing a statistical correction. This statistical correction defines a fade margin (FM). If the FM is equal to zero, radioelectric coverage is only guaranteed in 50% of the locations in the cell (defined in the DTM). The micro scalar quality is defined by the percentage of locations in the cell in which radioelectric coverage is guaranteed. This quality sets the fade margin that is considered in the link budget.

Assuming a log-normal distribution, the FM can be estimated by:

$$FM\ (\mathrm{dB}) = K(\mathrm{L})\cdot\sigma_{\mathrm{L}} \tag{1}$$

where σ_{L} (dB) is the variability of locations in the cell and K(L) is the normalized distribution abscissas for the percentage of locations (L). The K parameter is related with the inverse function of Gauss G^{-1}(L) by the expression:

$$K(\mathrm{L}) = \mathrm{G}^{-1}\ (1 - \mathrm{L}/100) \tag{2}$$

For calculations, a typical value for the UHF band in rural environments is a shadowing standard deviation with locations at 6 dB. If we fix a micro scalar quality of 90%, the fade margin is:

$$FM\ (\text{dB}) = 1.28\ 6 = 7.7\ \text{dB} \tag{3}$$

The macro scalar quality is the percentage of cells with radioelectric coverage within an area. This area could be delimited by a polygon, that represents a municipal or a regional area in our case. In our calculations, we assumed a macro scalar quality of 90% for the regional term and 85% for the municipal term.

2.6. Propagation Model

Many propagation models, such as the Longley–Rice [16], Bullington [17], Vogler [18], Luebbers [19], and Deygout [20] models, have been used for UHF band radio planning in rural environments in addition to the recommendations of the Radiocommunication Sector of the International Telecommunication Union (ITU-R) [8,9]. All these models estimate the mean value of the received signal in each cell of the DTM, taking into account the terrain profile between the transmitter and the receiver.

In the radio planning tool used, propagation loss is evaluated for each terrain profile by:

$$L\ (\text{dB}) = L_0 + \text{L}_{\text{Terrain irregularities}} + L_{\text{Close environment}} \tag{4}$$

where L_O is the free space loss, that can be calculated by:

$$L_0\ (\text{dB}) = 33.44 + 20 \log f\ (\text{MHz}) + 20 \log d\ (\text{km}) \tag{5}$$

$L_{\text{Terrain irregularities}}$ is the diffraction loss caused by obstruction of the terrain. For rural environments, this propagation loss can be estimated using the recommendation ITU-R P.526 [8]. $L_{\text{Close environment}}$ is the propagation loss taking into account the multipath phenomenon. This loss is directly related with the morphography in the vicinity of the mobile. In the GIS, a raster was created, with a resolution of 100 × 100 m, in which each cell has a value (in dB) representing the loss due to the type of environment (rural pine forests, suburban environment and urban environment). The Hata model [10] was used to estimate the value for suburban and urban environments. A measurement campaign, for the TETRA system (400 MHz), consisting of five routes, was carried out by the authors within a prototype—which included three base stations—to estimate the path loss for the rural (pine forest) environment. In Table 1, the obtained values for the TETRA system are shown. Moreover, in this table, the values for the LTE system (700 MHz), in which the losses for the rural environment were estimated by considering ITU-R P.833 [21], are also presented. These values were applied to the simulations performed in this study. Figure 4 shows a comparison between the propagation model and the measurements in one of the routes. Table 2 gives the mean error and standard deviation of the difference between the propagation model and the measurements for each route.

Table 1. Obtained path loss for the different types of environments considered.

Type of Environment	$L_{\text{Close environment}}$ (dB) (400 MHz, TETRA)	$L_{\text{Close environment}}$ (dB) (700 MHz, LTE)
No value	0	0
Rural (pine forest)	10	14.5
Suburban	13.75	13.76
Urban	25.65	27.52

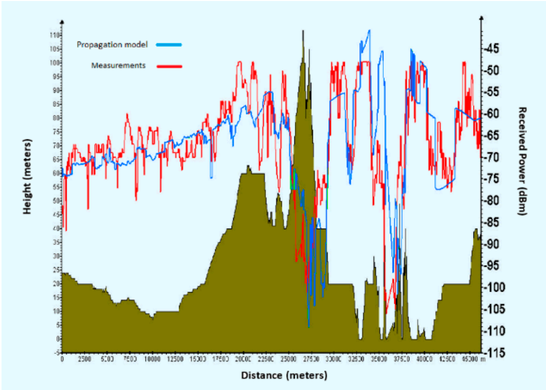


Figure 4. Comparison between measurements and the propagation model.

Table 2. Mean error and standard deviation of the difference between the propagation model and measurements for each route.

Route Number	Mean Error (dB)	Standard Deviation (dB)
I	1.04	8.34
II	8.96	9.20
II	3.63	8.45
IV	−0.44	7.58
V	10.65	12.19

2.7. Link Budget

Table 3 gives the link budget for the TETRA and LTE systems and for the downlink (DL) and the uplink (UL). The link budget was calculated for a mobile receiver, in which the antennas are mounted on a vehicle, with a gain of 2 dBi for the TETRA system and 3.5 dBi for the LTE system. Also, in the base station, the antennas have an omnidirectional pattern with a gain of 7 dBi for the TETRA system and a directional pattern with a gain of 15 dBi for the LTE system.

Table 3. Link budget for the TETRA and LTE systems.

			TETRA		LTE	
Parameter	**Units**		**DL**	**UL**	**DL**	**UL**
Power Tx	dBm	P_{tx}	44	40	35	28
Gain Tx	dBi	G_{tx}	7	2	15	3.5
Losses Tx	dB	L_{tx}	2	0.5	2	0.5
PIRE	dBm	$P_{tx} + G_{tx} - L_{tx}$	50	41.5	48	31
Fade Margin	dB	FM (90%)	7.7	7.7	7.7	7.7
Gain Rx	dBi	G_{rx}	2	7	3.5	15
Losses Rx	dB	L_{rx}	0.5	2	0.5	2
Bandwidth		BW	25 kHz		5 MHz	
Sensitivity	dBm	S	−103	−106	−95	−100
Lmax	dB	$PIRE - FM + G_{rx} - L_{rx} - S$	146.3	144.8	138.3	136.3

Radioelectric coverage was calculated for a rural environment, so a noise-limited scenario was assumed.

For the LTE system, the sensitivity is calculated by:

$$S\ (\text{dBm}) = -174 + F + 10 \log (Nrb \times RB) + SNIR \tag{6}$$

where F is the noise figure (7 dB for the DL and 2 dB for the UL), Nrb is the number of resource blocks (25 for a bandwidth of 5 MHz for the radio channel), RB is the bandwidth of each resource block (180 kHz), and $SNIR$ is the average signal-to-interference-and-noise ratio (5 dB)

In the proposed UL for LTE, a real throughput of 4.5 Mbps can be achieved with a sensitivity of −100 dBm using a 16 QAM modulation, allowing the transmission of full HD (1920 × 1080) video streaming. The maximum path loss (L_{max}) is in agreement with Dunlop et al. [22] for the TETRA system and with Elnashar et al. [23] for the LTE system. As seen in Table 3, for both systems, the worst case is the UL, and the maximum path losses that can be compensated for are 144.8 dB for the TETRA system and 136.3 dB for the LTE system. These values were used in the calculations for both systems.

2.8. Radioelectric Coverage Calculations

Using the radio planning tool, individual radioelectric coverage can be calculated for a site considering the maximum propagation loss allowed by the link budget. Then global radioelectric coverage is calculated taking into account the best server principle (the value of each cell covered by several sites is the best value). Each radioelectric coverage is stored in the GIS using a raster and a vector point layer. The raster had the same resolution as the DTM and the value of each cell was now the received power. The vector point layer also has an associated attribute table containing all the information used in the calculations: transmitter power, transmission loss, antenna gains, frequency, propagation model, etc.). This allows us to use all the facilities of GIS for managing and doing calculations with spatial data.

The percentage of radioelectric coverage can be easily calculated in GIS because the radioelectric coverage has been stored as a raster. The functionality of GIS [7] that allows operation between a raster and vector layer can be used to evaluate the macro scalar quality of service (defined in Section 2.5, using a raster of the global radioelectric coverage and the vector polygon layer of the municipal areas. The map of the macro scalar quality was also stored as a raster and can be represented and managed in the GIS environment.

2.9. Methodology for Planning the New LTE Network

The proposed flow-chart to plan the new LTE network can be observed in Figure 5.

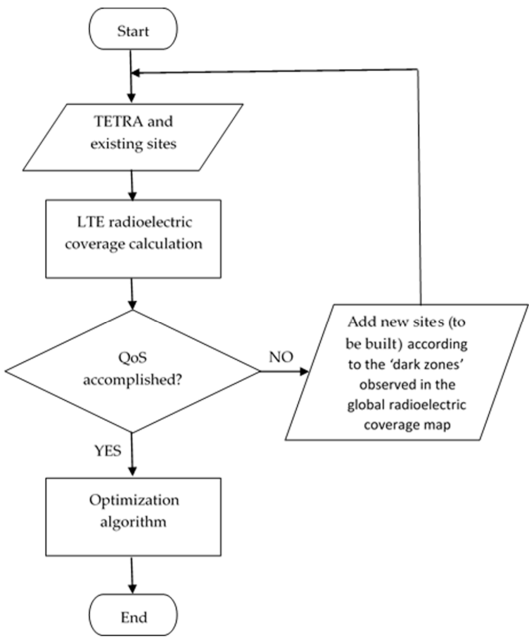


Figure 5. The proposed flow-chart to plan the new LTE network.

First of all, the LTE radioelectric coverage for each municipal area is calculated using the existing TETRA sites and the existing sites with other radiocommunication systems (not TETRA). In our case, this leads to 34 sites in total (16 TETRA base stations and the 18 existing sites) (Figure 3).

- If the QoS (see Section 2.5) is fulfilled, the following optimization algorithm can be applied: Initially, individual radioelectric coverages were calculated for the available sites and are ordered in a table from the least to the greatest radioelectric coverage. Then, an iterative process for each site was conducted starting with the first element (the one with the least radioelectric coverage) and the same sequential order (from top to bottom). In each iteration, the following steps are carried out:

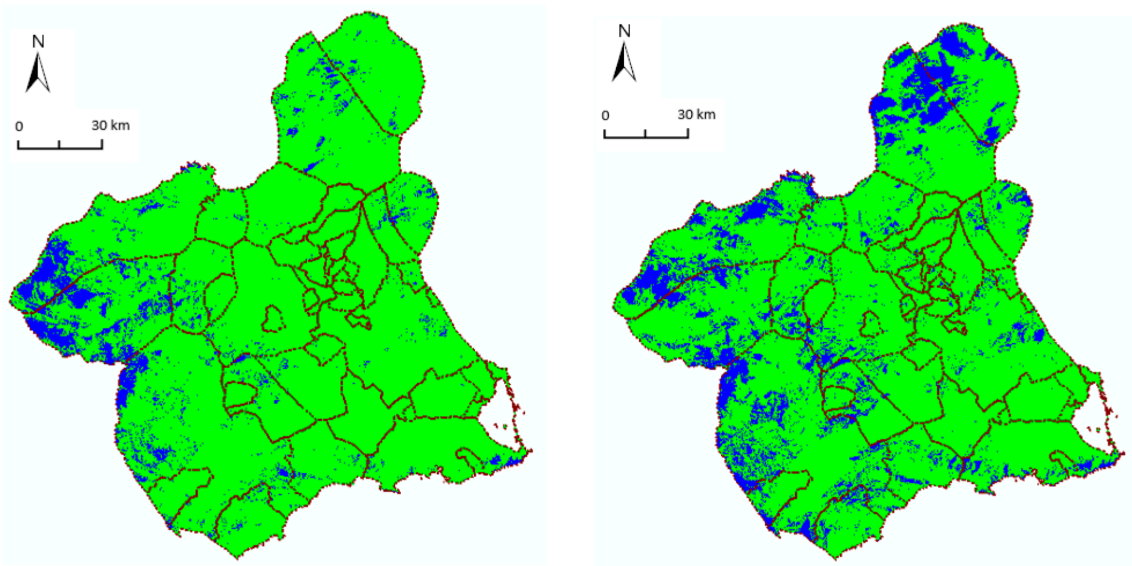
    1. The element of the corresponding table is discarded.
    2. The global radioelectric coverage is calculated with the sites not discarded or eliminated.
    3. If the macro scalar quality is accomplished for the region and the municipal areas, the site discarded in step 1 is eliminated and, if not, the site is kept in the table.

- If the QoS is not fulfilled, this fact means that more sites are needed. Therefore, the sites which do not exist yet but can be built with the necessary infrastructure (telecommunication tower, electrical line, stand, etc.)—the location of which is estimated according to the dark zones observed in the global radioelectric coverage map—should be progressively added until the QoS is accomplished. Then, the previously mentioned optimization algorithm can be applied.

3. Results and Discussion

3.1. The Existing TETRA Network

The radioelectric coverage is calculated using the 16 TETRA base stations (Figure 6a). Table 4 gives the percentage of radioelectric coverage for each municipal area. As can be observed, the macro scalar quality is above 90% for the region and 85% for the municipal areas.



(**a**) (**b**)

Figure 6. Radioelectric coverage for (**a**) the TETRA system (16 sites) and (**b**) the LTE system (34 sites).

Table 4. Percentage of radioelectric coverage in municipal areas.

Municipal Area	% TETRA Radioelectric Coverage (16 Sites)	% LTE Radioelectric Coverage (34 Sites)	% LTE Radioelectric Coverage (46 Sites)	% LTE Radioelectric Coverage (39 Sites) (Optimized)
Abanilla	95	87	87	87
Abarán	97	97	97	96
Águilas	89	87	87	87
Albudeite	100	94	94	94
Alcantarilla	100	100	100	100
Aledo	100	96	98	95
Alguazas	100	96	96	96
Alhama	94	97	97	96
Archena	100	95	95	95
Beniel	100	100	100	96
Blanca	99	96	96	96
Bullas	96	96	96	96
Calasparra	96	91	91	91
Campos del Río	100	98	98	98
Caravaca	93	79	85	85
Cartagena	95	90	90	88
Cehegín	90	85	85	85
Ceutí	100	93	93	93
Cieza	98	92	92	92
Fortuna	99	93	93	93
Fuente Álamo	99	98	98	98
Jumilla	87	75	92	92
Librilla	94	99	99	99
Lorca	90	78	85	85
Lorquí	100	97	97	97
Mazarrón	94	89	89	88
Molina de Segura	100	98	98	98
Moratalla	86	71	85	85
Mula	96	91	91	91
Murcia	96	94	94	92
Ojós	98	95	95	94
Pliego	98	95	95	95
Puerto Lumbreras	91	85	94	94
Ricote	98	97	96	95
San Javier	100	99	100	98
San Pedro del Pinatar	100	100	100	90
Torre-Pacheco	98	100	100	99
Las Torres de Cotillas	100	97	97	97
Totana	92	84	88	86
Ulea	100	98	97	96
La Unión	99	92	92	92
Villanueva	100	98	98	98
Yecla	90	73	91	91
Santomera	99	94	94	91
Los Alcázares	100	100	100	99
Region	93	85	91	90

3.2. The New LTE Network

The methodology proposed in Section 2.9 was applied in our case study. First, the radioelectric coverage for the new LTE network which will take into account the mentioned 16 TETRA sites, as well as the 18 existing sites (34 in total), was calculated (see Figure 6b).

It should be noted that the number of 'dark zones' (blue color in Figure 6) is greater for the LTE network than for the TETRA network. Table 4 shows the percentage of radioelectric coverage for each municipal area. The macro scalar quality of 85% for the municipal area is exceeded in the majority of cases, except for six municipal areas (Caravaca, Jumilla, Lorca; Moratalla, Totana and Yecla) out of 45. Furthermore, the percentage of LTE radioelectric coverage for the region is 85% (below the actual macro scalar quality of 90% for the TETRA network).

At this point, according to the flow-chart of Figure 5, new sites must be added to improve the radioelectric coverage. With the aid of the GIS, twelve more sites, represented as blue triangles in Figure 3, were found in the detected 'dark zones'. These new sites would have to be constructed with the necessary infrastructure (telecommunication tower, electrical line, stand, etc.). They were chosen because they are accessible by path, and it is easy for them to receive electric power. The new radioelectric coverage was calculated with the total 46 sites (Table 4). Now, the macro scalar quality of service is accomplished for the municipal areas and for the region, 85% and 90%, respectively.

The next step was to apply an optimization algorithm to see if the same quality of service could be maintained with fewer sites.

As can be observed in Table 4, 39 sites is enough to accomplish the QoS. These results indicate that the number of sites is a factor of 2.4 higher for the LTE network than for the TETRA network if we want to ensure the same macro scalar quality for both systems. Figure 7 shows the LTE radioelectric coverage with 39 sites, in which the dark zones have been reduced with respect to the case with 34 sites (see Figure 6b).

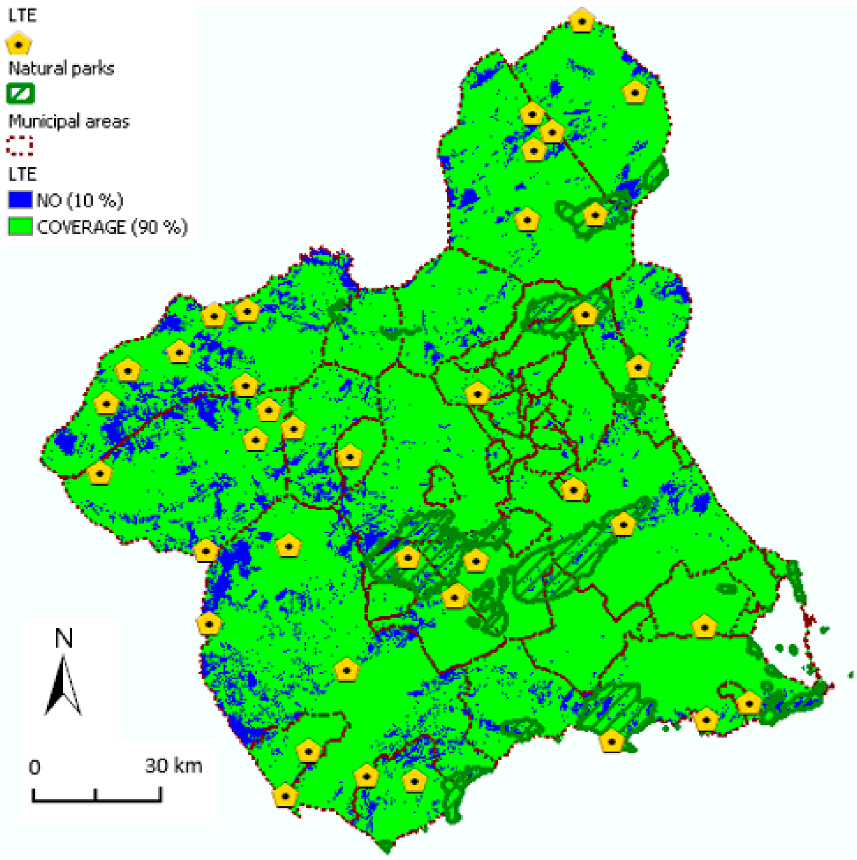


Figure 7. LTE optimized radioelectric coverage (39 sites).

We can also analyze other situations of interest for the PPDR agencies, such as the radioelectric coverage in natural parks (represented as polygons in Figure 7). Table 5 shows the percentage of radioelectric coverage for each natural park. The percentage of LTE radioelectric coverage is less than 85% for 6 of 20 natural parks (assuming either 46 or 39 sites), although the percentage of radioelectric coverage for municipal areas is equal or above 85% (see Table 4). Therefore, we need, in this case, to add several sites to improve the radioelectric coverage in these six natural parks.

Table 5. Percentage of radioelectric coverage in natural parks.

Natural Park	% LTE Radioelectric Coverage (46 Sites)	% LTE Radioelectric Coverage (39 Sites) (Optimized)
Enclavado	85%	85%
Sierra Salinas	97%	96%
Sierra de El Carche	88%	88%
Sierra de La Pila	90%	88%
Ribera de Cañaverosa	63%	63%
Cañón de Almadenes	53%	44%
Ajauque y Rambla Salada	99%	99%
Carrascoy y El Valle	92%	92%
Barrancos de Gebas	95%	95%
Sierra Espuña	81%	78%
Salinas y Arenales de San Pedro	100%	90%
Saladares del Guadalentín	100%	100%
Cabezo Gordo	97%	90%
Islas del Mar Menor	92%	92%
La Muela y Cabo Tiñoso	79%	79%
Calblanque	50%	40%
Sierra de las Moreras	73%	73%
Islas mediterráneo	97%	93%
Calnegre y Cabo Cope	88%	88%
Cuatro Calas	99%	98%
Total	86%	84%

4. Conclusions

The conversion of an existing TETRA network operating in the 400 MHz band to a new LTE network operating in the 700 MHz band has been analyzed in a real scenario by means of both simulations and measurements. The latter were used to tune the propagation models employed and, in this sense, the values of the obtained path loss for the different type of environments considered (morphographic correction) are offered for both TETRA and LTE systems. Moreover, the study of special scenarios such as natural parks has also been considered in the analysis.

The results show that, according to the real scenario considered, the number of sites needed in the LTE network—for a specific quality of service (90% for the whole region and 85% for municipal areas), is a factor of 2.4 higher than for the TETRA network.

Author Contributions: Investigation, D.d.R.C., L.J.-L. and J.V.R.

Acknowledgments: This work was supported by the MINECO, Spain under Project TEC2016-78028-C3-2-P.

Conflicts of Interest: The authors declare no conflict of interest.

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