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Procedures for planning and optimization of spectrum-monitoring networks in the VHF/UHF frequency range

SM Series

Spectrum management

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REPORT ITU-R SM.2356-1*

Procedures for planning and optimization of spectrum-monitoring networks in the VHF/UHF frequency range

(2015-2017)

Summary

This Report includes discussion on three different methods. The first combines angle of arrival (AOA) measurements from multiple sites using direction-finding antenna arrays to determine the emitter location. The second combines time difference of arrival (TDOA) measurements from a minimum of three sites (two pairs of TDOA measurements between the three sites are required for geolocation). The third method combines both AOA and TDOA measurements to perform geolocation processing (a minimum of two sites are needed: one with both AOA and TDOA capability, and one with TDOA capability only). This Report includes three annexes as follows:

Annex 1: Practical example on local AOA SMN planning at relatively plain terrain.

Annex 2: AOA SMN planning in mountainous and hilly regions.

Annex 3: Receiver performance and its impact on network coverage.

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[*] This Report should be brought to the attention of ITU-D Study Group 1.

1 Introduction

The goal of spectrum monitoring network (SMN) planning and optimization is to enable required monitoring functions across territories containing the highest density of transmitters with the minimum number of monitoring stations. This is to be achieved using the lowest possible antenna tower heights while maintaining high quality RF measurements. The territory of interest may be centres of high population or industrial development.

The computerized methodology for such planning and optimization in the VHF/UHF frequency ranges (based on angle of arrival (AOA) principals) was developed over recent years and set out in section 6.8 of the ITU-R Handbook on Spectrum Monitoring (2011 edition). It marks a major step forward in comparison with previous procedures based exclusively on expert assessments by the network designers. Recommendation ITU-R SM.1392-2 alludes to section 6.8, and emphasizes the potential technical and economic benefits of effective planning and optimization of SMNs in developing countries. These benefits can only be achieved using computer – aided methods and apply in full measure to developed countries as well.

Practical experience has shown that, with the right computer models and calculations, it is possible to reduce the number of fixed monitoring stations required for coverage of a given region in comparison with SMNs planned on the basis of expert assessments. This is achieved by selecting the best sites for stations and optimal heights of the antennas, also taking into account particular features of the surrounding terrain.

On the other hand, it is clear from the practical experience of implementing that methodology using suitable software[1], as applied to SMNs of different composition and deployed under differing geographical conditions, with differing levels of financial capabilities of administrations, that the planning and optimization process is rather complex. It comprises many different stages and is determined by the primary requirements of the planned SMN, which have to be defined in advance. In addition, it will be necessary during the planning stage itself to tackle a number of administrative decisions to optimize the process. All these aspects are not well addressed in existing guidance.

For this reason, it would be useful to supplement the current accepted methodology with a more detailed guideline and step-by-step implementation to make the entire process more effective, while minimizing the work involved. This issue is the subject of this Report.

The combination of two or more geolocation technologies when designing an SMN is an option. There are a number of different methods available for geolocation processing. This Report includes discussion on three different methods. The first combines AOA measurements from multiple sites using direction-finding antenna arrays to determine the emitter location. The second combines time difference of arrival (TDOA) measurements from a minimum of three sites (two pairs of TDOA measurements between the three sites are required for geolocation).

The third method combines both AOA and TDOA measurements to perform geolocation processing (a minimum of two sites are needed: one with both AOA and TDOA capability, and one with TDOA capability only). For simplicity these three methods are referred to as:

- AOA;
- TDOA, and
- Hybrid AOA/TDOA.

Finally, consideration should be given to receiver performance factors such as Noise Figure/sensitivity, Phase Noise, etc. Higher performance receivers may allow greater separation and

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[1] Software such as described in Annex 5 of the ITU-R Handbook on Computer-Aided Techniques for Spectrum Management (CAT) (edition 2015).

thus a lower number of monitoring stations to cover a particular territory. This report includes three annexes as follows:

Annex 1: practical example on local AOA SMN planning at relatively plain terrain

Annex 2: AOA SMN planning in mountainous and hilly regions

Annex 3: Receiver performance and its impact on network coverage

2 Fundamental decisions by an administration in the course of preparation to the planning process

The first step in SMN planning requires basic decisions concerning the system objectives, configuration and performance in light of the available and projected financial resources. Apart from the points referred to in Recommendation ITU-R SM.1392-2, these include:

– **The size of the territory to be monitored**

This means the overall area to be covered by monitoring.

– **Blanket vs. local coverage of territory by fixed stations**

Should coverage of a given territory be blanket or local, and is this to be achieved by individual local subsidiary networks that provide blanket coverage only within the confines of their segment of the overall monitored territory?

– **AOA vs. TDOA vs. Hybrid AOA/TDOA technology**

Considering Report ITU-R SM.2211-1, a study of the geolocation requirements is needed to determine what technologies are most suitable for the development of a particular SMN.

– **Deciding whether to build a new SMN vs. upgrading an existing SMN**

The administration must decide to what extent existing fixed stations should be reused in the new SMN, and whether their equipment need to be replaced or upgraded to enhance coverage.

– **Categories of test transmitters and the core monitoring tasks: listening, measurement of emission characteristics, direction finding (DF), and estimation of emitter location**

Within areas of blanket (or near-blanket) coverage, it is important to determine the required coverage areas of the four referenced monitoring functions in relation to the categories of different test transmitters (see § 3.1 below), and monitoring frequencies. Combined approaches are possible. For example, it is possible to specify a requirement for blanket location coverage for higher category test transmitters (such as category II), and blanket DF-only coverage for lower-category transmitters (such as category I).

– **Relative proportions of fixed and mobile station numbers**

Given that DF homing of an emission source requires a mobile station, it is essential to determine the appropriate ratio of fixed and mobile stations. This will depend on some factors including the monitoring function used for blanket (or near-blanket) coverage. With location blanket coverage, the likely coordinates of an emission source will be known from the intersection of lines of bearing from fixed stations. In this case, fewer mobile stations will be needed and DF homing completed rapidly. In the case of DF-only blanket coverage, homing becomes more laborious and time-consuming. Because of this, a higher ratio of mobile stations will be needed. More mobile stations are needed in the case of extensive areas with no DF coverage by fixed stations.

Decisions made at the beginning of the planning process can be changed in light of knowledge obtained during the planning process and considering the status of financial resources.

In the initial phase of planning, it is also important to gather as much information as possible about the region of interest (administrative, socioeconomic, etc.), including:

- detailed maps indicating centres of population, existing roads, railway lines, etc.;
- density distribution of population and economic zones across the region;
- density distribution of transmitting systems in the region;
- data from the national frequency register on the disposition and technical characteristics of high-power transmitters and their antenna heights;
- maps indicating routes of high-tension electrical transmission lines and associated switching stations;
- data on the locations of microwave antenna masts and other tall metallic structures, if available.

It is also important to make decisions concerning the following:

- **Determining the requirements for radio monitoring equipment**

  To determine the boundary values of the field strength it is necessary to set performance requirements for the monitoring station equipment such as the receiving antenna gain, cable attenuation, receiver sensitivity, etc.;

- **The choice of radiowave propagation model**

  Planning the SMN is greatly affected by the RF propagation models used. Therefore, it is important to choose a model appropriate for the monitoring station service area. Information about propagation models can be found in section 6.4 of the ITU-R Handbook of Spectrum Monitoring (2011 edition). For example, propagation models based on the methodology set out in Recommendation ITU-R P.1546-5 or P.1812-3 may be used. Practice shows that calculations according to Recommendation ITU-R P.1546-5 often give a more accurate prediction for quasi-plane relief, while Recommendation ITU-R P.1812-3 is more suitable for hilly and mountainous terrain. However, these models are not always accurate, as each prediction is highly dependent on the specific situation.

  For urban areas, propagation models developed specifically for these conditions such as Okumura-Hata, or COST 231 Walfisch-Ikegami model should be used. New deterministic propagation models have been developed which utilize three-dimensional digital maps of cities and buildings. Many of these models are based on methods of geometrical optics (e.g. ray tracing models) and are potentially more accurate than classical methods.

- **Determining avoidance areas for monitoring stations**

  It is important to determine areas to avoid placement of monitoring stations. These areas can be closed or secure locations, or areas with high field strength. In the second case, a boundary field strength (a root-sum-square value) for signals within the passband of the monitoring receiver is 30 mV / m, (i.e. 90 dB (μV/m), according to § 2.6 of the ITU-R Handbook). Recommendation ITU-R SM.575-2 can be used for the calculation of boundary field strength necessary to protect fixed monitoring stations against interference from nearby or strong transmitters.

- **Location uncertainty (for AOA/TDOA SMNs)**

  When planning AOA/TDOA stations, it is necessary to determine the maximum allowable error value of an emitter’s position. This error value will define the basic performance requirements of the monitoring network. It is worth noting at this point that the AOA method needs at least two monitoring stations, whereas the TDOA method needs at least three stations.

It is also essential to obtain statistics (over several years) for the region concerned, on requests for monitoring services that can be provided only with mobile stations (for example, searches for illegal transmitters, resolution of interference cases, etc.). Such statistics can be used to determine the optimal mix of fixed and mobile stations.

3 Planning and optimization of AOA SMNs

3.1 Main principles of the existing general methodology

The methodology presented in section 6.8 of the ITU-R Handbook on Spectrum Monitoring (2011 edition) is based on the calculation and subsequent analysis of four distinct monitoring coverage areas. These each require different levels of sensitivity in the monitoring receivers. The first three functions are:

- Listening (receiver sensitivity at maximum – furthest range)
- Emission characteristic measurement (receiver sensitivity at lower level – lower range)
- Direction Finding – DF (receiver sensitivity at lowest level – lowest range). Table 6.8-1 of the ITU-R Handbook on Spectrum Monitoring (2011 edition) assumes, for purposes of comparison, the following field-strength threshold values at the respective coverage zone boundaries:
  - 0 dB(μV/m) for listening,
  - 12 dB(μV/m) for emission characteristic measurement, and
  - 20 dB (μV/m) for DF.

For planning purposes, it is possible to adopt other boundary field-strength values, depending on the equipment characteristics and the methodology for measuring emission characteristics which are to be used in the SMN. These coverage zones are independent for each SMN station, and merging them together gives the overall respective coverage zones for each monitoring function.

The sizes of the zones are determined in essence by the topography of the area where the SMN is set up, the heights of the station antennas and the power and antenna heights of the transmitters to be monitored. A suitable model of radiowave propagation is provided by Recommendation ITU-R P.1546-5, Annex 5. In § 1.1, it describes a special method of calculation that is recommended for monitoring purposes. Recommendation ITU-R P.1812-3, as well as some other propagation models (see § 2 above), can also be used.

Table 6.8-1 of the ITU-R Handbook on Spectrum monitoring (2011 edition) proposes three categories of low-power “test transmitters” with relatively low antennas that can be used to model, simulate, and plan SMNs.

These e.i.r.p. categories are as follows:

- Category I

  Power 10 W, antenna height 1.5 m (private mobile radio (PMR)) transmitters carried in light vehicles).
- Category II

  Power 10 W, antenna height 20 m (PMR base stations, low-power broadcasting transmitters, TV transponders).
- Category III

  Power 20 W, antenna height 40 m (same transmitter type as in category II but with somewhat greater power and antenna height).

An SMN will obviously be more effective monitoring powerful transmitters with greater antenna heights.

The fourth monitoring function is location. The location coverage zone, critical to the topology of fixed stations in the SMN, is based on triangulation, and corresponds to the overlapping DF coverage zones of at least two stations in an SMN. As the distances between stations increases, the size of the overlapping DF zones (i.e. location coverage area) rapidly diminishes to nothing. A characteristic of the location coverage zone is that the location uncertainty (or accuracy) can vary widely within that zone, which is not usually the case with the other three monitoring functions. It varies, sometimes widely, within the zone, forming a so-called “location coverage template” (LCT) which is described in detail in section 4.7.3.1.4 of the ITU-R Handbook on Spectrum Monitoring (2011 edition).

At any point in the LCT, the location uncertainty value depends on a number of factors, the main ones being the following (see Fig. 1):

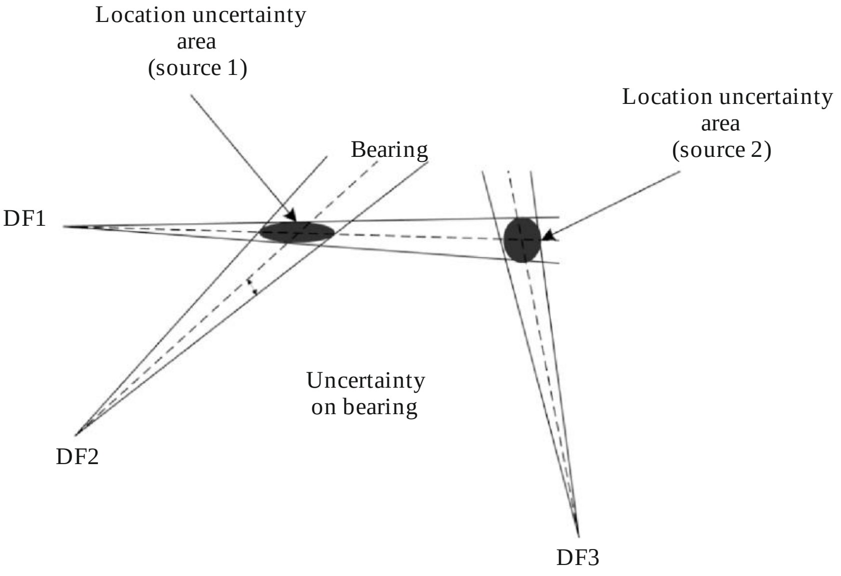
– the DF bearing uncertainty values for the direction finders used in triangulation, which result in the creation of sectors in which the individual bearing lines are distributed by angle;

– the distances from the direction finders to the intersection zones of the bearing line distribution sectors;

– the intersection angles of the bearing line distribution sectors.

FIGURE 1

Factors influencing location uncertainty values for radio emission sources



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Thus, the LCT is the most critical to a range of factors, and this must be taken into account in the process of planning the SMN. The LCT is also the best indicator of quality, both of the whole SMN and its different parts.

Of great importance for planning is the overall DF coverage zone of the fixed stations, since in this area, these stations provide bearings, which simplify DF homing of emission sources by mobile stations interacting with fixed stations.

According to section 6.8 of the ITU-R Handbook on Spectrum Monitoring (2011 edition), in cases requiring blanket monitoring coverage over a significant area, in which a large number of fixed stations is needed, planning of a suitable SMN can be based on the theory of regular networks as set out in Report ITU-R BS.944. Such an approach enables us to create an SMN with fairly large distances between stations in rural areas and smaller distances in urban or industrial areas, where the density of transmitters subject to monitoring is high.

3.2 Computer-aided modelling of an SMN

The basic steps are:

1) defining the objective;
2) assessing the monitoring coverage of existing stations;
3) creation of a primary regular network;
4) assessment of the monitoring coverage by stations in the primary regular network and optimization of the number of stations and their characteristics;
5) subdivision of individual primary network cells and further optimization of the number of stations and their parameters;
6) refining individual station sites and characteristics in a computer model.

Each of these steps will be discussed in greater detail.

3.2.1 Defining the objective

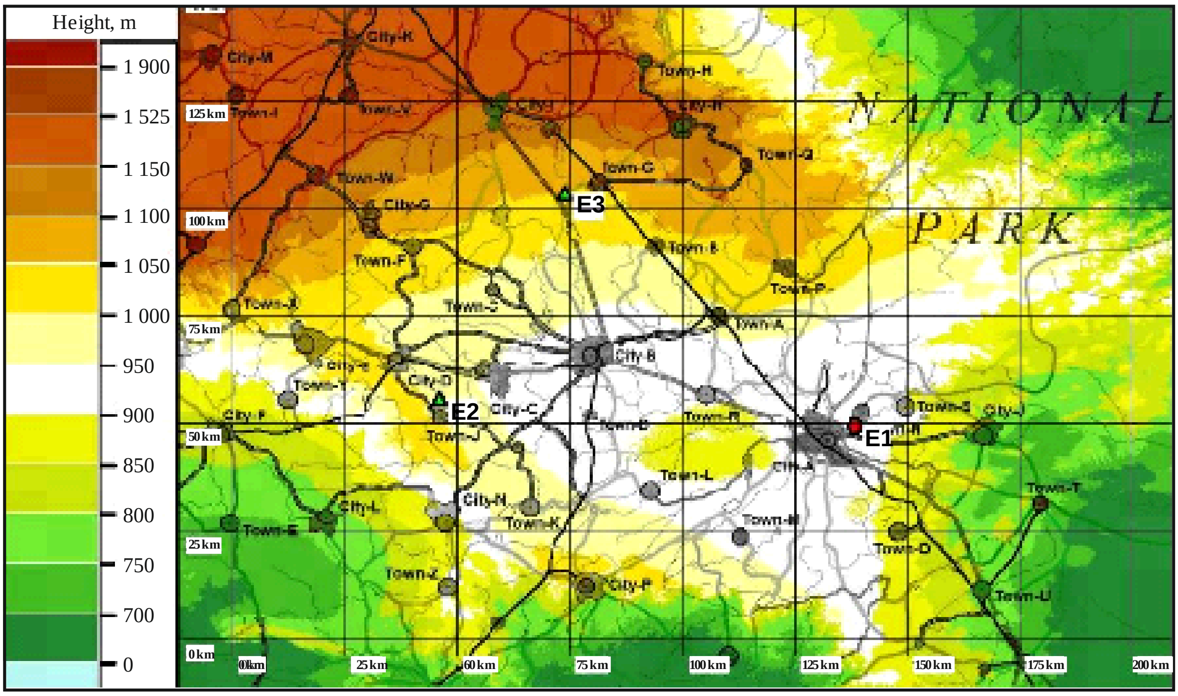
Once these, at least preliminary, key decisions have been made and the necessary data have been collected, the work of computer-aided modelling of the future SMN can begin. A specific example of a desired SMN will be used to illustrate the stages in the planning process.

Let us suppose that an administration wishes, in the light of available financial resources, to develop a new SMN in a populated area of the territory shown together with its topography in Fig. 2. Assume that, in the area concerned, there are already three fixed stations (E1-E3) with fairly modern equipment (DF uncertainty of 1° r.m.s.), and these have to be incorporated in the planned SMN without any upgrade. The antenna heights of these stations are 30 m for station E1 and E2 and 20 m for station E3, and no change is envisioned.

It is also assumed that a decision is made to ensure blanket coverage, for all monitoring functions including location, of the populated part of the territory in question for category II test transmitters (i.e. power 10W, antenna height 20 m). In addition, the most economically developed part of the territory, situated between City A and City E, is to have blanket coverage at least for a DF function for category I transmitters (power 10W, antenna height 1.5 m). It is estimated that future equipment will ensure DF accuracy of 1° r.m.s.

FIGURE 2

The area in question with the three existing stations



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Thus, for the purpose of computer modelling (see Figs 2 and 3) we have the following initial conditions:

1) Existing SMN – three fixed stations (E1-E3):
   - station E1 – antenna height 30 m;
   - station E2 – antenna height 30 m;
   - station E3 – antenna height 20 m;
   - DF uncertainty 1° r.m.s.
2) New SMN requirements:
   - blanket coverage of populated part of territory with all monitoring functions including location for category II transmitters (power 10 W, antenna height 20 m);
   - blanket coverage of territory between City A and City E at least for DF for category I transmitters (power 10 W, antenna height 1.5 m);
   - DF uncertainty 1° r.m.s.

3.2.2 Initial SMN modelling

3.2.2.1 Assessing the monitoring coverage of existing stations

The coverage zones of the existing stations are calculated for different monitoring functions with the aid of computer software with at least the features described in Chapter 5 of the ITU-R Handbook on Computer-Aided Techniques for Spectrum Management (2015 edition).

For the example considered here, the coverage zones of all the existing stations for listening, emission characteristic measurement and DF are shown in Fig. 3, and for location (i.e. LCT) in Fig. 4. Calculations are made for 450 MHz and category II test transmitters. That frequency is used below in all subsequent calculations unless otherwise specified. Green areas in Fig. 3 correspond to coverage in respect of the most sensitive function (listening), pink areas represent coverage in respect of the somewhat less sensitive function of emission parameter measurement, and yellow areas indicate DF coverage, the least sensitive function. The LCT (distribution of location uncertainties shown by the colour gradations in Fig. 4) is calculated for a 50 per cent probability of locating the sought transmitter in the corresponding uncertainty ellipse (see section 4.7.3.1.4 of the ITU-R Handbook on Spectrum Monitoring, 2011 edition).

The boundaries of the joint DF coverage zone (shown in yellow in Fig. 4) are traced by a red line in Fig. 4, while in Fig. 3 the red line represents the boundaries of the LCT given by the assembly of coloured zones in Fig. 4.

Figure 4 shows that the location coverage offered by the existing stations even with regard to category II test transmitters is very far from meeting the given requirements.

The conclusion is obvious in this particular case, even without any detailed calculations. In other cases, however, when the objective is to optimize an existing reasonably dense SMN, such calculations are crucial and can be used as the basis for subsequent steps in computer-aided modelling.

FIGURE 3

Overall monitoring coverage zones of the three existing stations

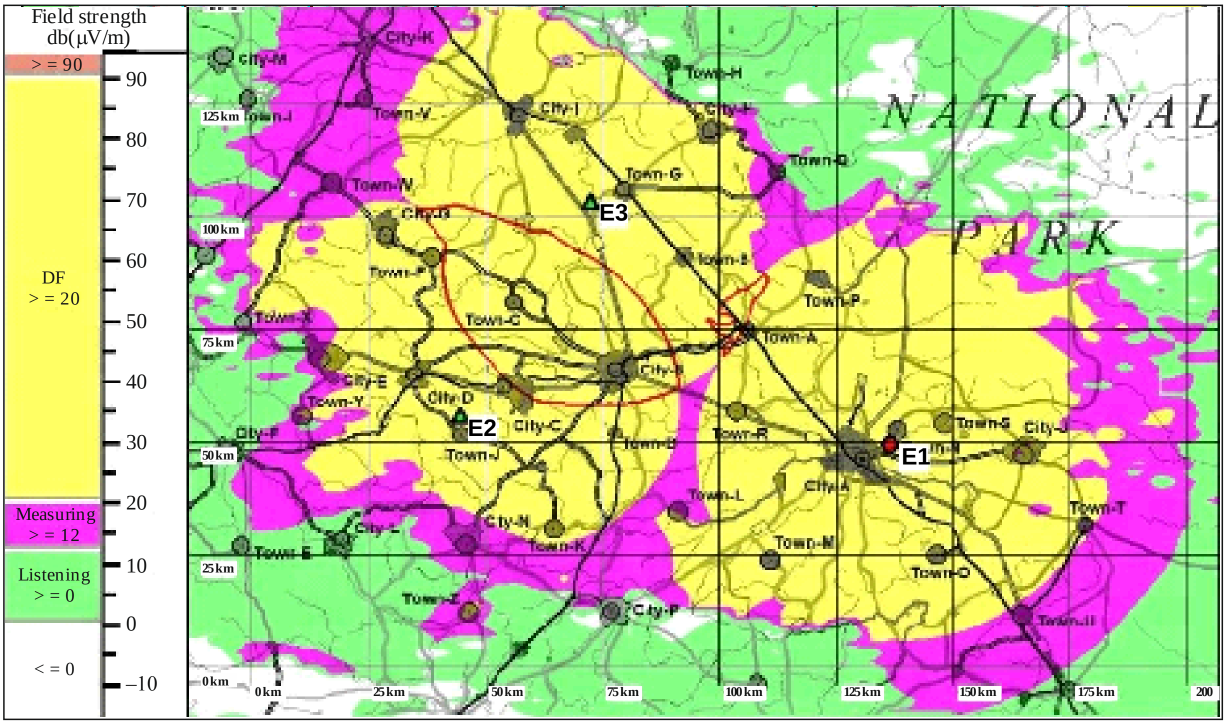

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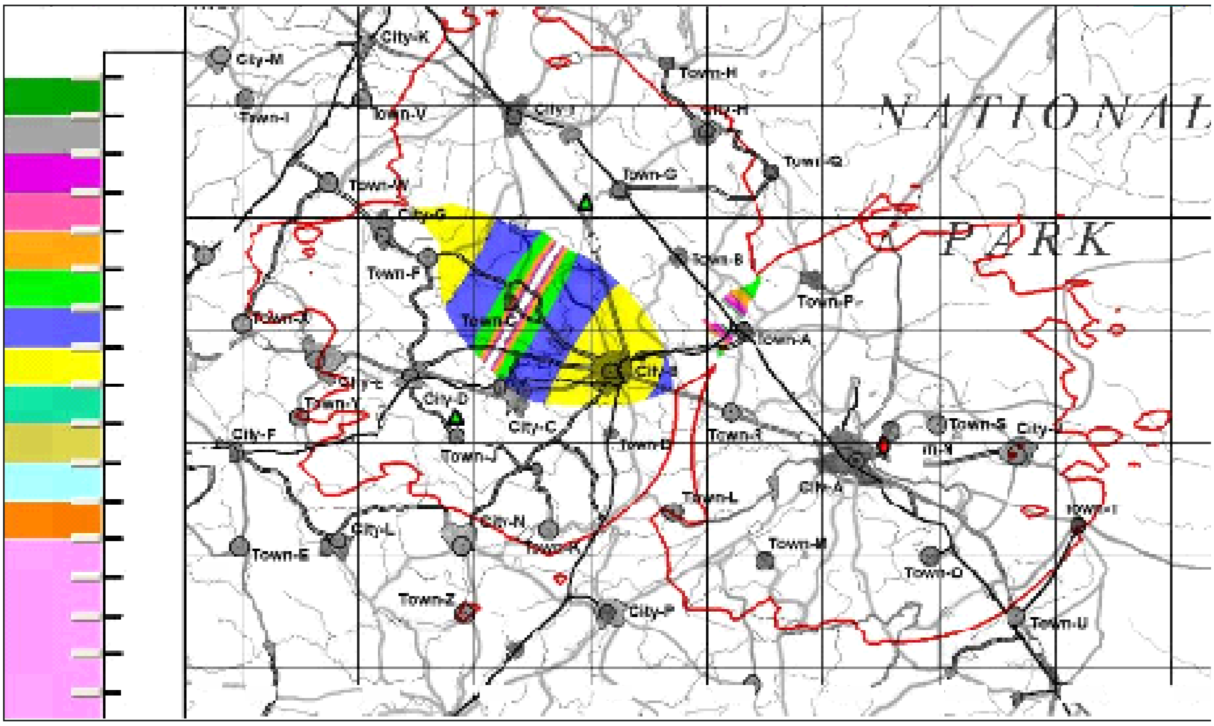
FIGURE 4

Location coverage template for the three existing stations



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3.2.2.2 Superimposition of a primary regular network

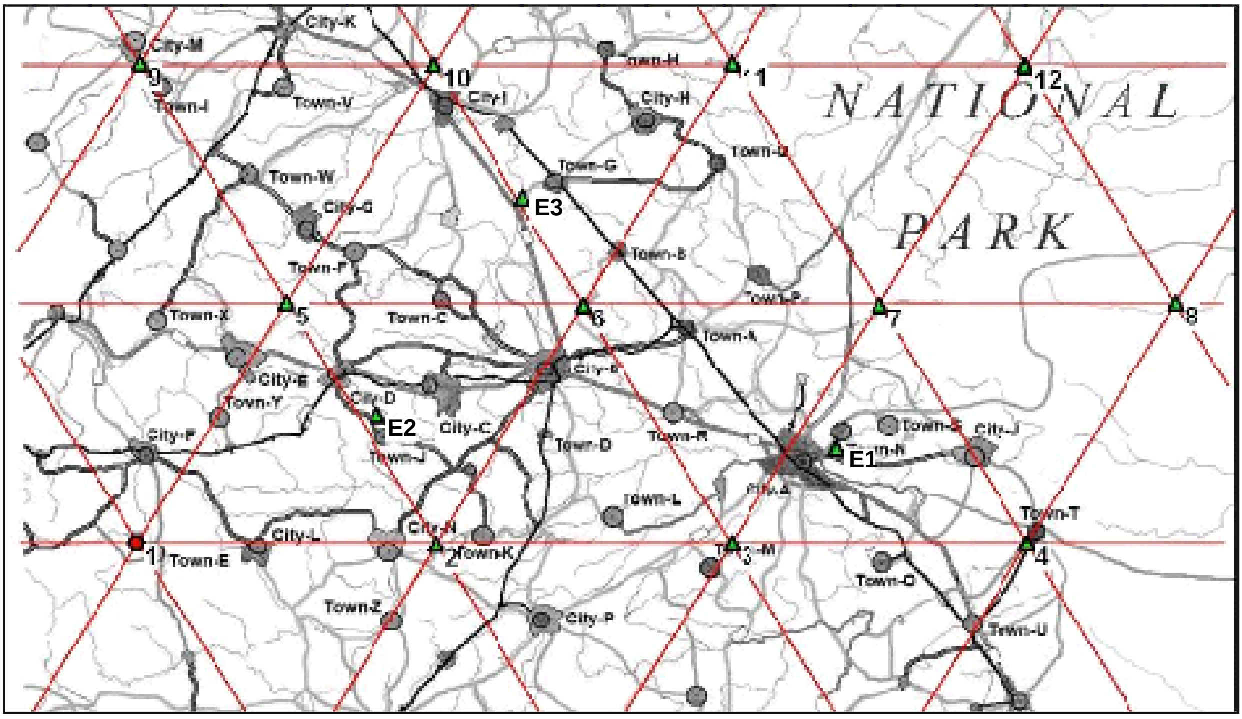
A primary regular network is overlaid on the territory under consideration, with distances of 60 km between nodes. Monitoring stations are sited virtually at the network nodes. There are innumerable different options for arranging nodes in a regular network of this type in relation to population centres and other geographical objects. These nodes may, for example, be arranged so as to coincide with or be close to existing stations, or located around the territory of greatest interest in terms of monitoring.

Let us suppose that a decision is made to arrange the network nodes in accordance with the second of the above options, siting them around the territory which includes Cities A to E as shown in Fig. 5, with virtual siting of 12 additional stations at the network nodes. The existing stations are close to the nodes of secondary regular network elements with distances between nodes of 30 km, which are considered in § 3.2.2.4.

Looking at Fig. 5, it can be seen that stations 8 and 12 could be excluded from any further considerations in the interests of economy, as they are on the National Park territory which has no centres of population and therefore does not require monitoring by fixed stations.

FIGURE 5

Primary regular network



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3.2.2.3 Assessment of monitoring coverage by stations of the primary regular network; optimization of station numbers and characteristics

We then proceed to the next step, calculating the coverage zones for different monitoring functions of stations located at the nodes of the primary regular network, together with existing stations. The results of this process are used to further optimize the number of stations, if it is possible to do so at this stage.

Figure 6 shows the results of calculations to ascertain coverage with different monitoring functions for category II test transmitters and antenna heights of all new stations of 30 m, while Fig. 7 shows the corresponding LCT. It is evident from Fig. 7 that with this number of stations and the configuration of the planned SMN, blanket location coverage is almost fully achieved for category II test transmitters. It is also evident from Fig. 7 that station 11 does not contribute significantly to location coverage of the neighbouring territories and can be eliminated in order to reduce system costs. Station 7 serves sparsely populated areas at the boundary of the National Park and can also be eliminated. If further cost reductions have to be made, we may consider eliminating station 4, also on the boundary of the National Park.

Figure 8 shows the monitoring coverage of this primary network for category II test transmitters once stations 11, 7 and 4 have been eliminated. Removal of station 4 results in loss of location service for City J, although the latter remains covered by DF. However, City J will have location coverage for category III test transmitters, as can be seen from Fig. 9. Figure 9 illustrates better location coverage in the south-eastern and south-western parts of the region that now includes several more cities and towns.

FIGURE 6

Monitoring coverage of the primary network for category II test transmitters

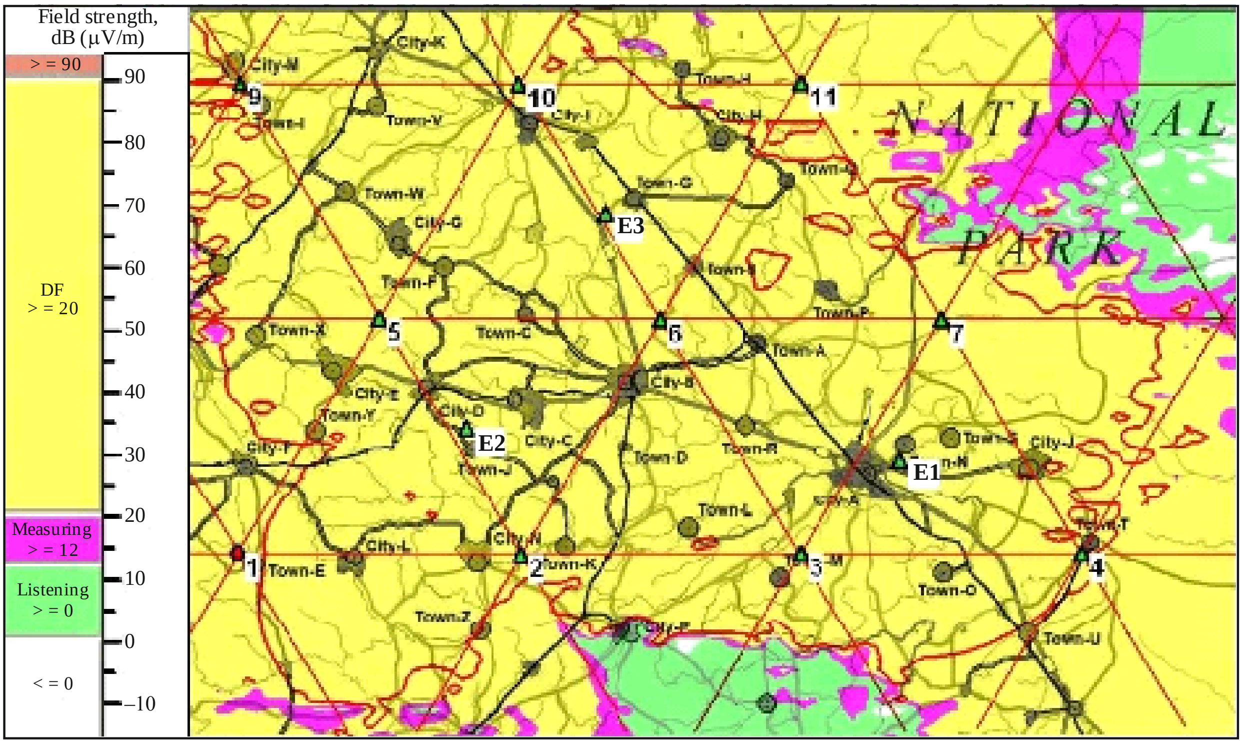

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FIGURE 7

Location coverage template of the primary network for category II test transmitters

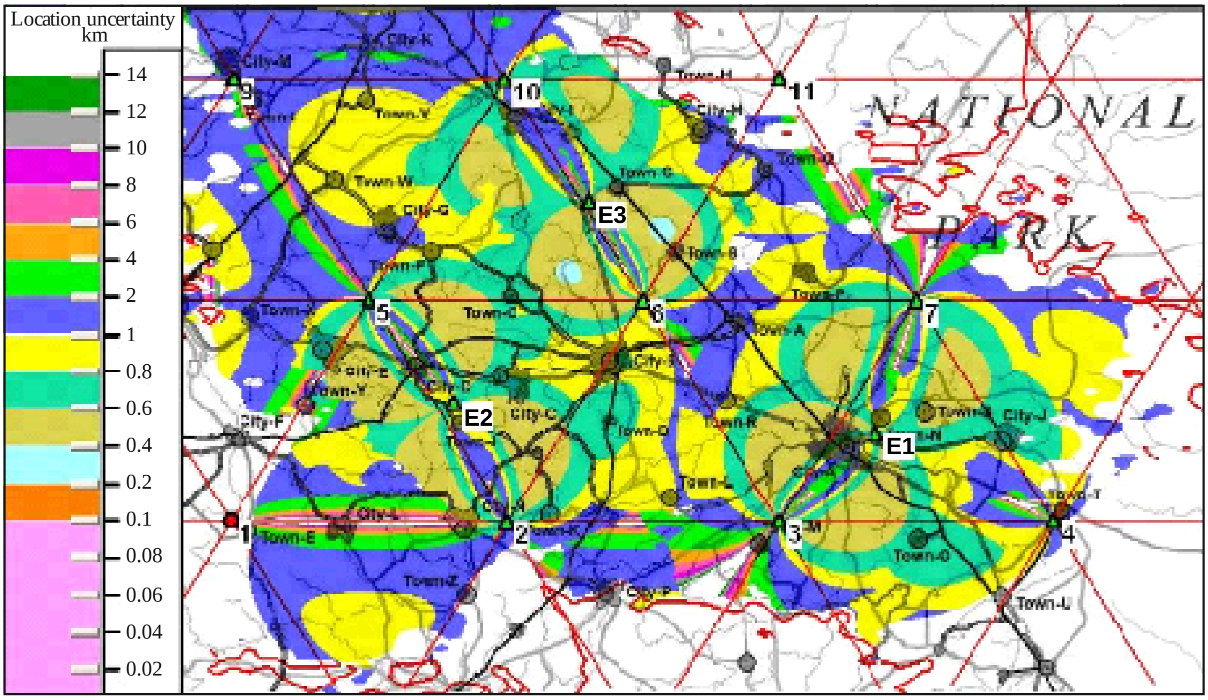

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FIGURE 8

Location coverage template of the primary network (minus stations 4, 7 and 11) for category II test transmitters

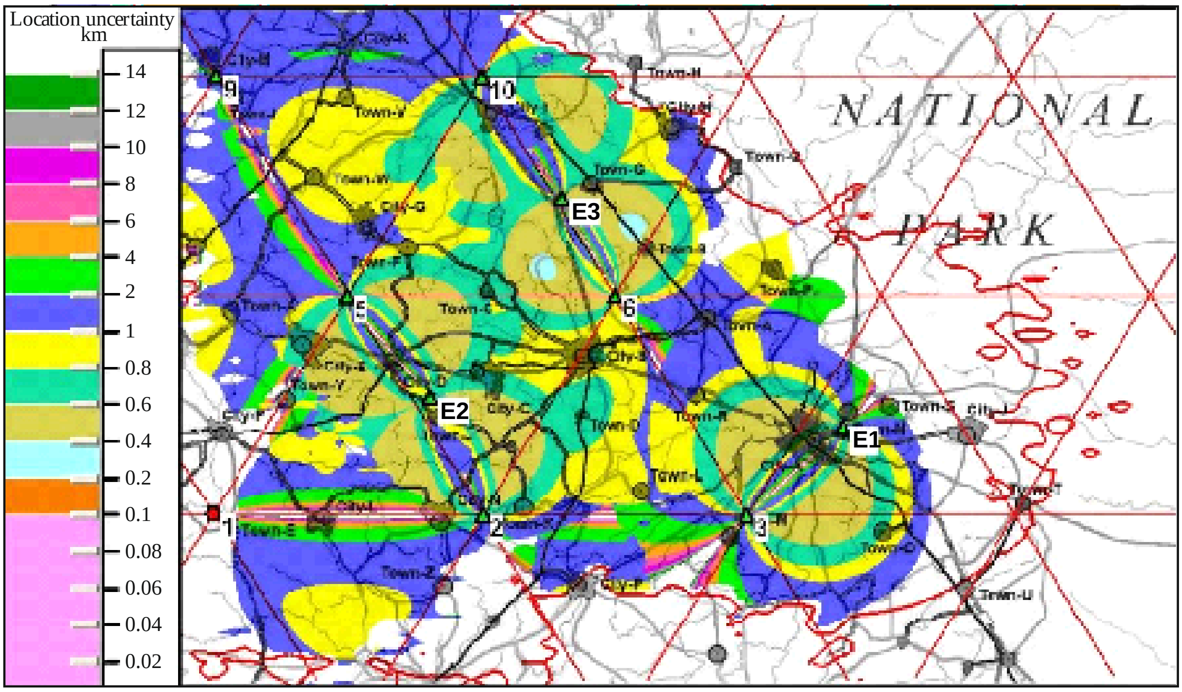

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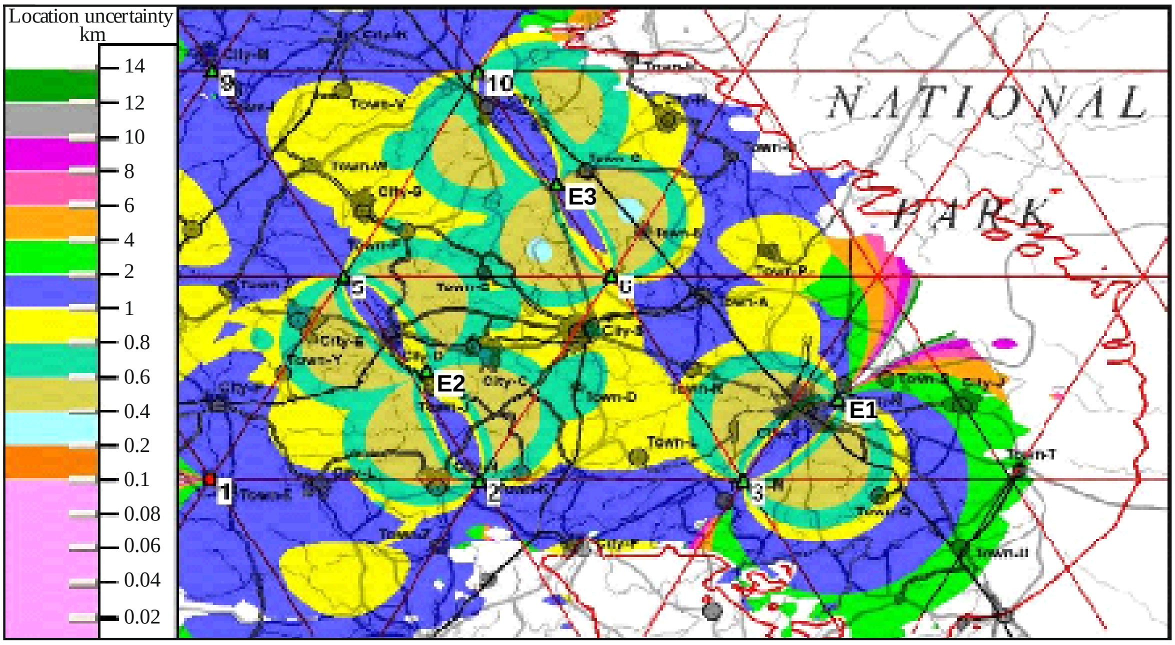
FIGURE 9

Location coverage template of the primary network (minus stations 4, 7 and 11) for category III test transmitters



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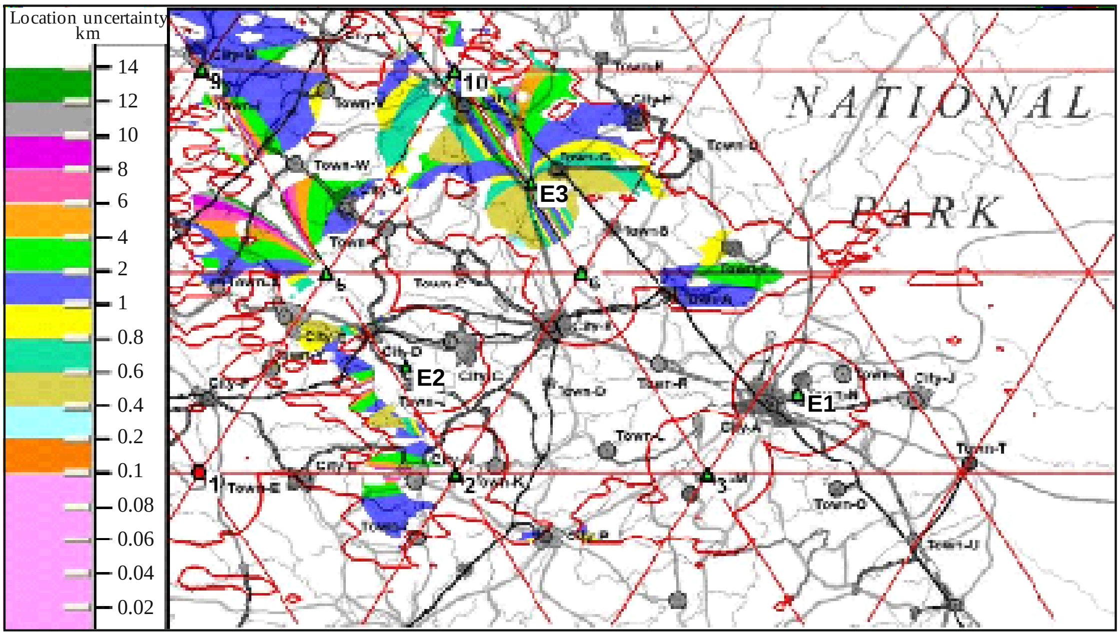
With these data, the administration can decide whether or not to retain station 4 in the planned SMN. A decision can be postponed until planning of the entire SMN is completed (see subsequent stages), the total number of stations determined and the available and projected funding accounted for. It may be considered preferable not to include this station during the first stage of the SMN development and, instead, leave it to subsequent stages.

If we compare Figs 8 and 9, it is interesting to note that the considerable increase in power and antenna height between category II and category III test transmitters, has little impact in terms of improving coverage in the north-eastern and southern parts of the region (around Town H and City P, respectively). In the first case, this is the result of a sharp reduction in the average height of the territory. In the second case, it is a result of an increase in average height of the territory, as we can see in Fig. 2. These significant effects obviously cannot be determined in more detail without appropriate calculations.

DF and location coverage in the SMN (minus stations 11, 7 and 4) for category I test transmitters is shown in Fig. 10. It is clear that the SMN, with regard to category I test transmitters, fails to achieve the objective of more detailed monitoring of the area between City A and City E. It is therefore necessary to increase the density of the primary network within the area in question.

FIGURE 10

Location coverage template of the primary network for category I test transmitters



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3.2.2.4 Subdivision of individual primary network cells and further optimization of the number of stations and their parameters

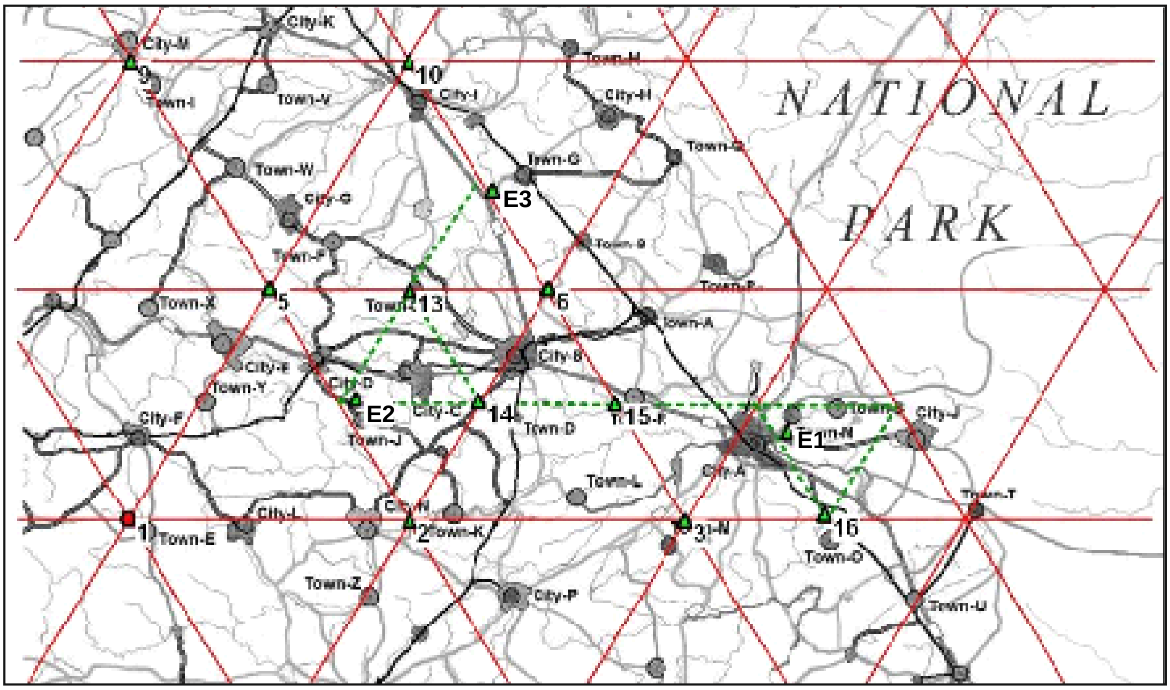
In order to increase the density of this part of the SMN, individual triangular cells in the primary network can each be subdivided into four triangular secondary network cells with distances of 30 km between stations, and additional stations should be sited at all or some of the new cell nodes.

In the example considered here, one possible option, which seems optimal in terms of economy, is shown in Fig. 11 by the broken green lines.

One primary triangle outlined by stations 2, 5 and 6 is subdivided into four secondary triangles, for which only two new stations (13 and 14) are required, since the existing station E2 is used as the third. In each of the other four primary triangles, only one secondary triangle is defined, and in three of these the existing stations E1 and E3 are used.

FIGURE 11

Primary network with secondary network elements



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The joint DF coverage in this denser SMN for category I test transmitters is shown in Fig. 12, and location coverage is shown in Fig. 13. It is clear from these figures that the SMN thus obtained in essence meets the stated requirements, although there are small areas, to the south-east of City B, with coverage only with respect to emission characteristic measurements (areas shown in pink in Fig. 12). On the other hand, these areas without DF coverage for category I test transmitters disappear once we use test transmitters of 10 W and antenna heights of 5 m (single-story buildings with 2 m antennas sited on the roof), as it is clear from Fig. 14.

If it is desirable to reduce the size of these areas lacking coverage for category I test transmitters, the antenna heights of future stations 3 and 15, and of existing station E1, if necessary, can be increased to 50 m. Figure 15 shows the improved monitoring coverage when the antenna heights of these stations are increased to 50 m.

Figure 13 clearly illustrates the influence of topography on monitoring coverage. Territories situated north of a straight line connecting stations 5, 13 and 6 are significantly better covered by DF and location than territories south of that line, despite the considerably lower density of monitoring stations, including new ones, in that area. This is due to the fact that the northern part of the considered region is on high ground while the central part is in a valley (see Fig. 2). Such specific monitoring coverage features of this territory also cannot be identified by other means except by particular calculations.

In these particular geographical conditions, the northern part of the region is well served even for the location function as regards category I test transmitters. Considering this, the administration may want to ensure the same coverage in the central area between City A and City E. This can be achieved in one of two ways. First, we may attempt to divide a few more primary triangles into four secondary ones – for example, the triangles outlined by stations 2, 6 and 3, as well as stations 6, 3 and the previously excluded station 7, and to put additional stations at a number of nodes of these secondary triangles. Calculations show, however, that this solution is not effective.

The second option is considerably more effective and generally applicable. It involves dividing some secondary triangles (with inter-station distances of 30 km) located between City A and City E into tertiary triangle elements with inter-station distances of 15 km. This allows elimination of some of the primary network stations such as stations 2 and 3 as well as secondary network station 16. Coverage of the southernmost part of the region will be somewhat worse than before, but that may be considered an acceptable loss, taking into account the relatively low population density.

FIGURE 12

Monitoring coverage of the denser SMN for category I test transmitters

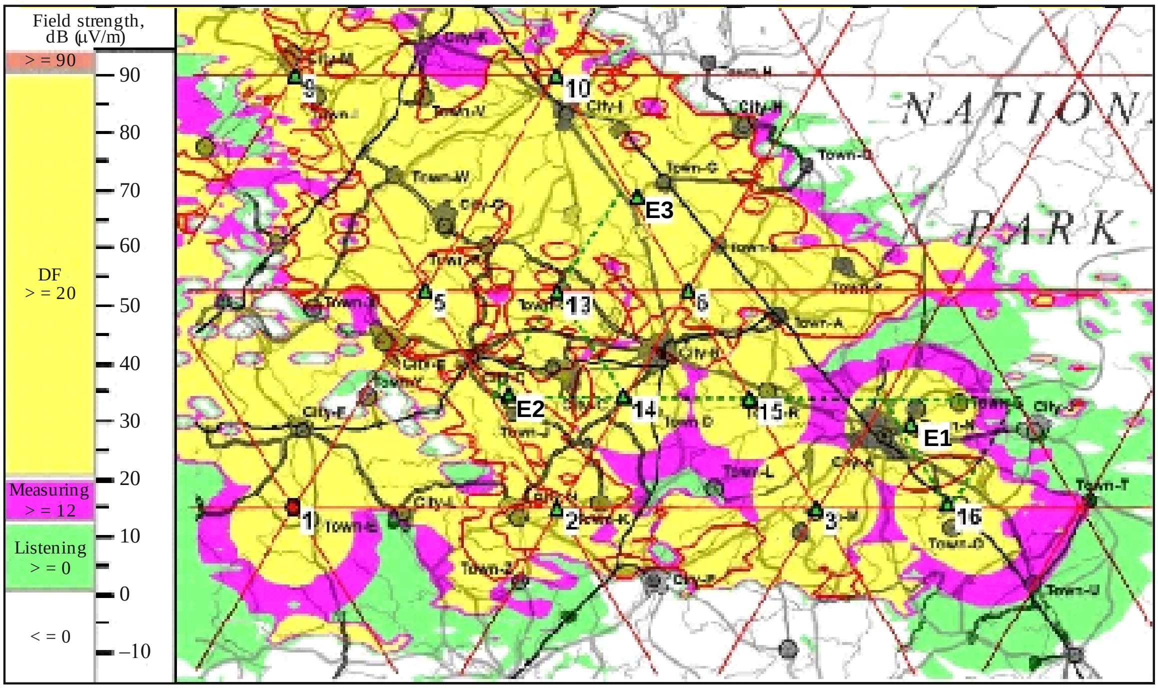

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FIGURE 13

Location coverage template of the denser SMN for category I test transmitters

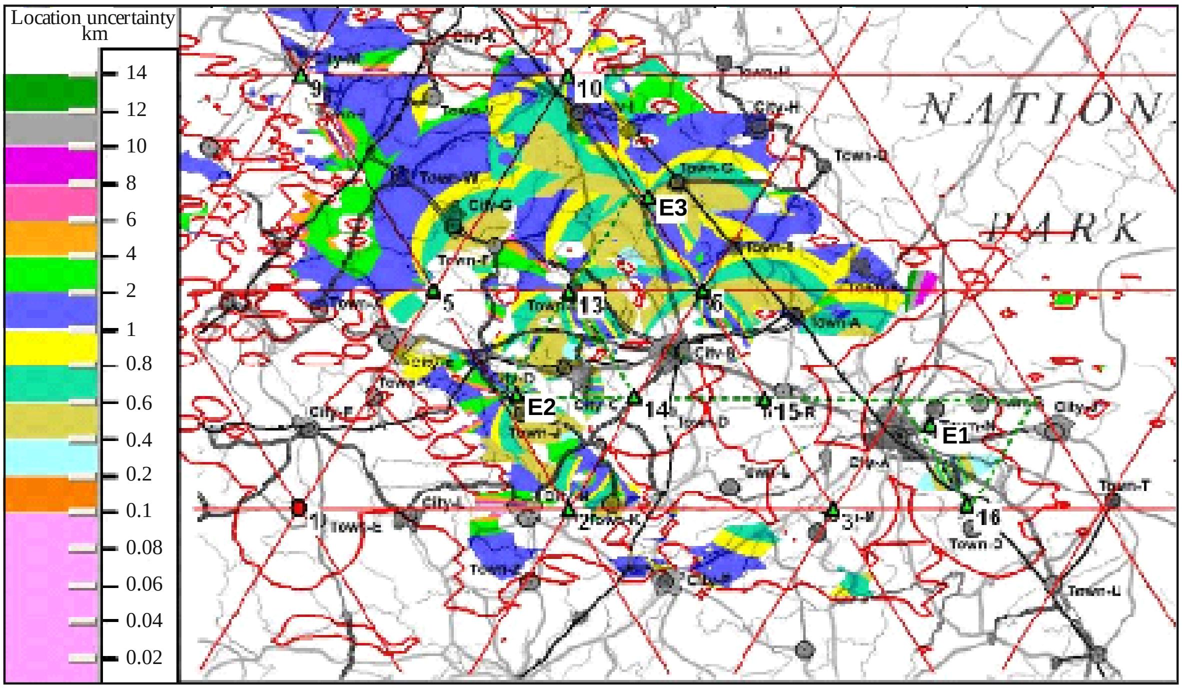

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FIGURE 14

Monitoring coverage of the denser SMN for 10 W test transmitters with antenna heights of 5 m

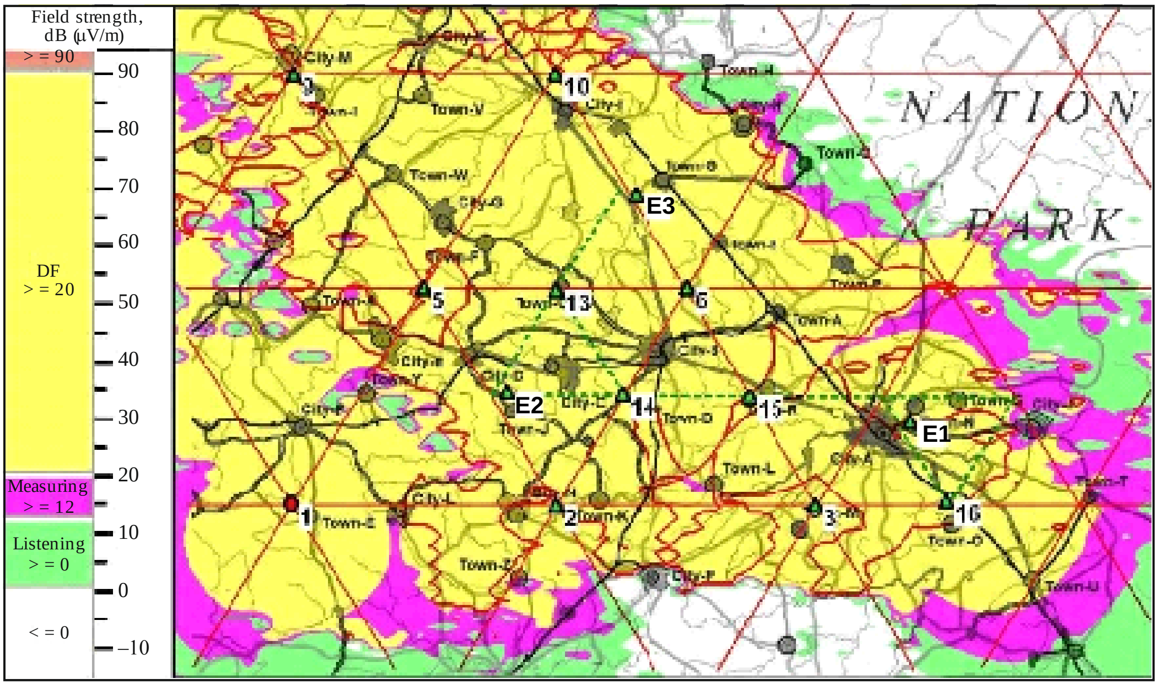

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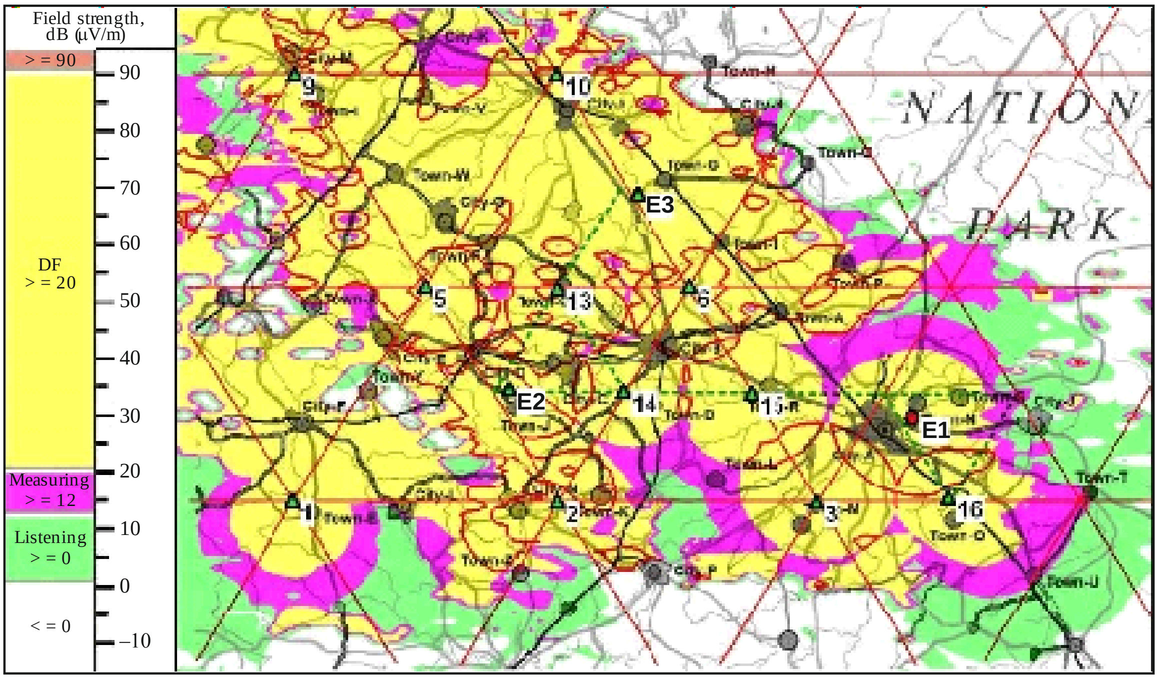
FIGURE 15

Monitoring coverage of the denser SMN for category I test transmitters when the antenna heights of stations 3, 15 and E1 are increased to 50 m



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It follows from the above that, in principle, there are many possible solutions, however each of them can be easily analysed by coverage calculations to identify the particular one that the administration can accept as the best in the situation.

The above figures and their analysis clearly show that the LCT is the best indicator of quality of the SMN as a whole and of its individual parts.

3.2.3 Refining sites and parameters of stations in the computer model

Once a preliminary decision has been made regarding the configuration of the SMN, the desired parameters and locations of the stations can be defined in a computer model.

First, the stations which are intended to carry out all monitoring functions need to be identified. Generally, stations can fall into one of three categories: attended, remote-controlled, or DF-only stations (these being exclusively remotely controlled). It can be noted that in the primary network with distances between stations of 60 km, practically all stations must carry out all monitoring functions, as otherwise there will be areas not covered by measurement of emission characteristics or even by listening. In the secondary network, with distances between stations of 30 km, some stations may be exclusively remote-controlled DF.

For example, calculations show that in the SMN example considered here, stations 6, 13 and 16 can be remote-controlled direction finders. In the tertiary network, with distances between stations of 15 km, many of the stations can be remote-controlled direction finders. The denser the SMN, the more stations can be remote-controlled direction finders.

In order to determine which stations can be remote-controlled direction finders, it is necessary to calculate the coverage zone for emission parameter measurement of some particular station located within a group of other stations. In the present example, this is seen as the pink zone with yellow DF coverage zone at its centre. We then have to ascertain which of these stations fall within the boundaries of this zone at a reasonable distance from its outer boundaries.

These stations can be regarded as potential remote-controlled direction finders, which can be confirmed through calculations of their individual coverage zones.

At this stage, it is also helpful to determine which of the stations performing all monitoring functions must be attended in order to effectively carry out the subsequent site surveys (see § 3.3 below). It is desirable to locate attended stations in or near larger cities in order to ensure a supply of qualified staff and infrastructure.

Also, it must be taken into account that modern IT makes it possible to situate a station operation centre in atypical urban neighbourhood using containerized remote-controlled station equipment and antennas sited outside the city. This solution simplifies the task of finding suitable plots of land and enables considerable cost reduction with regard to site acquisition, construction and installation costs. If, however, we site the operation centre in a tall building in an urban area, the antenna can be installed on the roof, which obviates the need to acquire a site for that purpose. However, it should be kept in mind that attended stations must have storage areas for mobile and transportable monitoring stations, such as garages or permanent parking places.

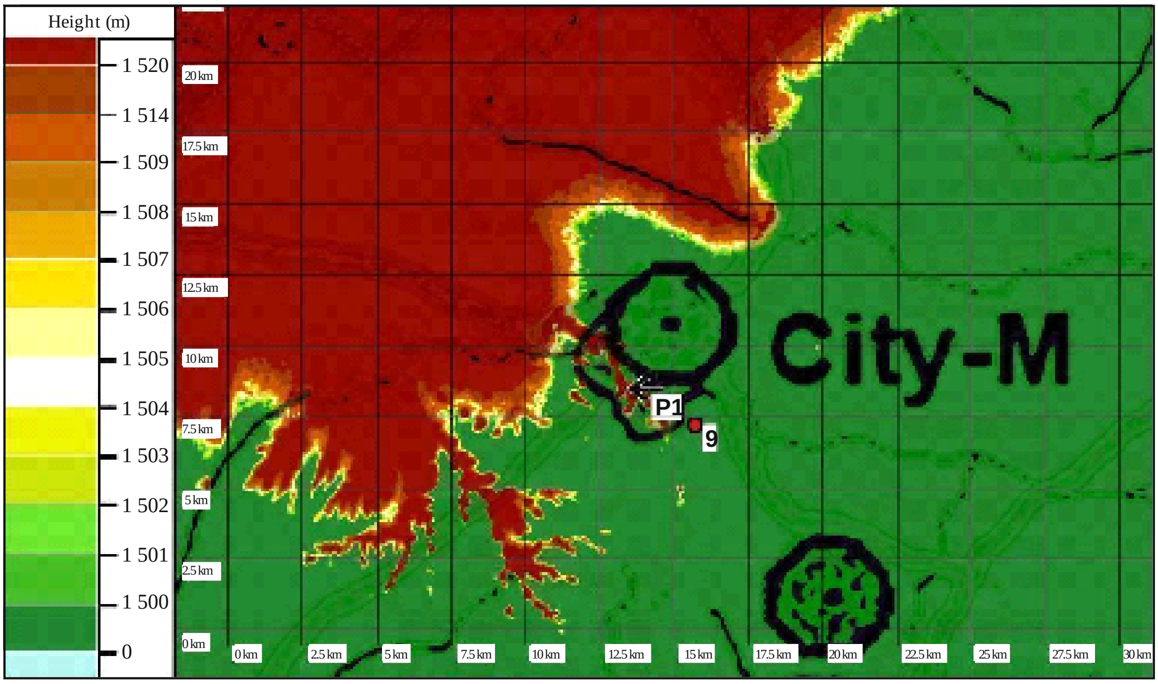
The distance between attended stations should not exceed 600 km, based on the consideration that mobile stations can be expected to service points no more than 300 km from their bases in the course of one working day (and then only if the roads are good).

Now it is possible, even at the computer modelling stage, to optimize the station parameters and site locations. For example, successive calculations can be used to ascertain the monitoring coverage zones of stations both individually and collectively and thereby optimize their antenna heights. Where the SMN is denser, the antenna heights of some stations can be lowered from 30 m (on which the original calculation was based) to 20 m and in some cases to 10 m, enabling the administration to make savings in terms of antenna masts. In the case of other stations, in order to increase their coverage zones where it is necessary to do so, antenna heights can be increased to 50 m, which in many cases can be achieved more effectively by moving the antenna to higher ground than by increasing the physical height of the antenna mast. This requires a detailed study of the topography around the previously determined site in order to identify suitable areas of higher ground.

As an example, Fig. 16 shows a magnified view of the topography in the vicinity of station 9. It clearly shows that at the pointer P1, only about three kilometres from the calculated station site, there is an area of high ground extending towards the north-west. P1 site is about 20 m higher than the calculated site of station 9, and moving station 9 to the higher ground will therefore significantly increase its monitoring coverage zones even with a reduced antenna mast. Figure 16 shows that there are a number of other high points west of station 9, and thus numerous possible ways of extending the station’s monitoring coverage zone by relocating it.

FIGURE 16

Topography in the vicinity of station 9



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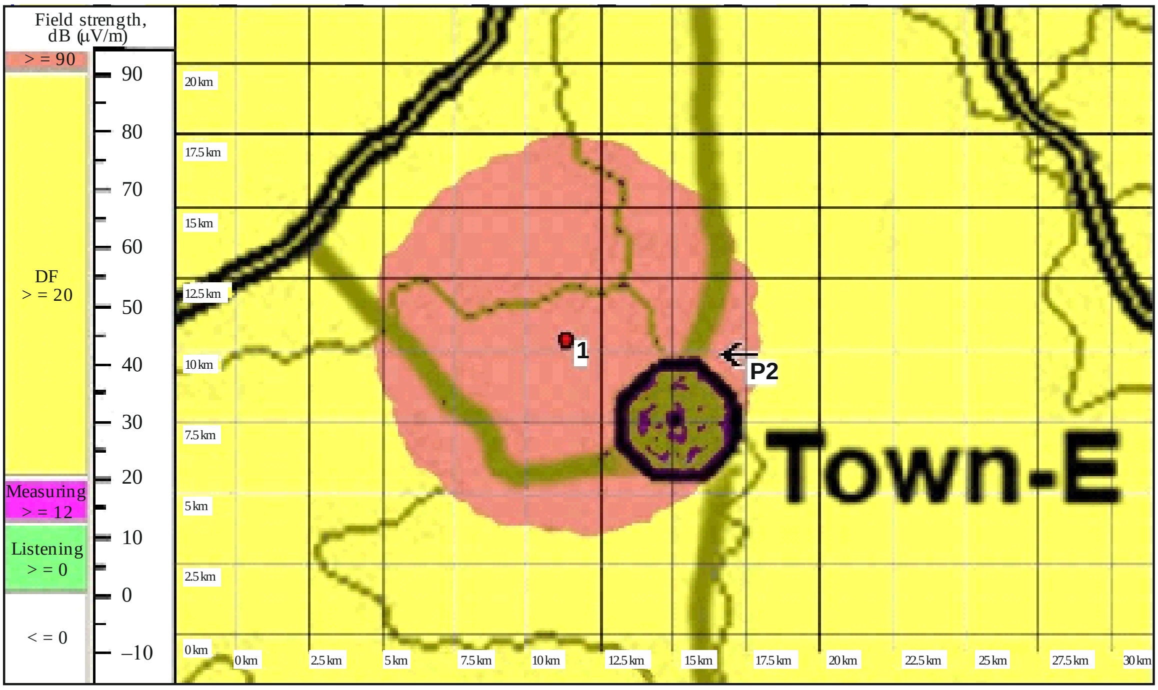
In addition, considering the data collected on the region in question (see § 2 above), the virtual location of each station in the model can be examined and optimized with regard to protection from interference and unwanted influences from nearby buildings and other structures, in accordance with Recommendation ITU-R SM.575-2 and section 2.6 of the Handbook on Spectrum Monitoring (2011 edition).

For example, consider the case of a 500 W radio broadcasting transmitter operating on 110 MHz, antenna height 50 m, placed in accordance with a national frequency assignment register at the site indicated by pointer P2 in Fig. 17. If we calculate the coverage zone for station 1 in relation to a test transmitter of the given parameters, with a boundary field strength of 30 mV/m, i.e. 90 dB (μV/m), then we find that the transmitter is within this zone (shown in brown in Fig. 17). It thus generates a field strength at the site of station 1 which exceeds the permissible level (see § 2.6 of the ITU-R Handbook on Spectrum Monitoring, 2011 edition). In order to overcome this problem, station 1 must be moved at least about 1.2 km to the west.

FIGURE 17

Interference protection zone of station 1



Report SM.2356-17

Similarly, the locations of the other stations in the model must be checked to ensure that they are situated beyond specified minimum distances from high tension electrical transmission lines, electrified rail lines, tall metal masts, etc., based on reliable data on these features. If necessary, stations in the model can be moved to other sites which then also need to be optimized on the basis of calculations of the corresponding monitoring coverage zones, as described above.

The result of all these operations provide a completed computer model of the configuration of the planned SMN which should be further refined through site surveys in the field.

3.3 Refining station sites in the course of site survey and land acquisition

All potential monitoring station sites identified by computer-aided modelling have to be meticulously surveyed to ensure that they comply with the protection criteria given in Recommendation ITU-R SM.575-2 and § 2.6 of the ITU-R Handbook on Spectrum Monitoring (2011 edition), and to ensure that it is possible to carry out the construction work needed to create the necessary infrastructure. Regarding infrastructure, the first requirement is to ascertain the feasibility of ensuring a mains power supply and creating access roads.

Unsurfaced tracks (“dirt roads”) can be used, if absolutely necessary, for access to remote unattended containerized stations. For attended stations, larger plots and surfaced roads are needed, as well as mains, water and sewerage. Consideration should also be given to physical site security, even for containerized sites, around the clock, in which case a minimal level of vital infrastructure must be maintained.

An appropriate methodology for site surveys and reporting results is described in detail in Annex 1 of the ITU-R Handbook on Spectrum Monitoring (2011 edition).

The site survey may reveal that site locations selected in the computer model cannot, for a variety of reasons, be used in practice. For example, they may not meet criteria for protection from interference or extraneous influences, or may not be usable due to the difficulty of providing the necessary infrastructure, etc. In majority of cases, however, the most common problem is simply a lack of suitable sites for sale. Possible difficulties in finding appropriate sites are referred to in Recommendation ITU-R SM.1392-2. The degree of difficulty naturally varies from one country to another, depending on specific social and economic conditions, legislation and administrative regulations, etc.

For this reason, the site surveying process may identify other potential sites that are available and more suitable in practical terms. Control calculations of their monitoring coverage zones must then be carried out. It may well be that, in order to maintain the required radio monitoring coverage at a new site, the antenna height (for example) will have to be increased. The administration must then decide whether to increase the antenna height, accept a reduced coverage zone, or find a new site altogether.

It follows that surveying a given site is not, in most cases, a one-step procedure and it has to be repeated, sometimes several times. This also entails repeated calculations of the monitoring coverage, the results of which are crucial in selecting the best site.

It may be impossible to find a location suitable for a new monitoring station near the desired site where interference levels are below the requirements established by § 2.6 of the ITU-R Handbook on Spectrum Monitoring (2011 edition). If this is the case, locations should be considered that minimize the field strength level of the interfering signals (even though they are in excess of 90 dB (μV/m)) and avoid the use of active antenna elements (see section 2.6.1.4 of the Handbook).

Only when the step-by-step process of site surveys, calculation of coverage and site acquisition have been completed the SMN planning process can be considered as completed. Then it is possible to call for tenders for the necessary civil engineering work and purchase of monitoring equipment, in accordance with the guidelines set out in Annex 1 to the ITU-R Handbook on Spectrum Monitoring (2011 edition).

Once the SMN has been planned, the final detailed calculations of monitoring coverage can be carried out for different frequencies (given that coverage tends to deteriorate as frequency increases) and for test transmitters operating at different power levels and with different antenna heights. These calculations can be used to compile a "monitoring coverage atlas" for the SMN which will be its unique technical "coverage footprint". The atlas will clearly indicate areas lacking coverage under specific conditions and parameters (frequency, test transmitter power, antenna height, and so on), which require greater attention in planning the operation of transportable and mobile monitoring stations. This is especially important in areas of broken or mountainous terrain.

The results of these final calculations also help to optimize the mix of fixed, transportable and mobile stations in the SMN. Generally speaking, the more sites that are not served by fixed stations, the more transportable and mobile stations will be required to maintain the required effectiveness of the SMN as a whole. In areas of the SMN that may not be covered by fixed stations (for example, in higher frequencies of the UHF range and in low-lying areas), it may be necessary to set up transportable stations in order to carry out various measurement campaigns. The optimal sites for these transportable stations can also be determined in advance by relevant calculations. In addition, longer time-frames must be allowed for the operation of mobile stations in these non-covered zones.

3.4 Planning small and special local SMNs

3.4.1 Planning small SMNs and those for big cities

We have considered the process of planning and optimizing a fairly large regional SMN. If on the other hand we need to plan or optimize a small isolated SMN consisting of two or several stations (not more than about five), the procedure can be considerably simplified. In this case, we can start by siting virtual stations in the computer model at convenient sites without creating a regular network overlay and then optimize the resulting SMN starting at the stage described in § 3.2.2.3 above. Example of practical planning procedures for local monitoring networks at a relatively plain terrain is presented in Annex 1.

In large cities, DF is considerably complicated by multiple reflections. To improve the reliability of DF, and thus also of location, and to allow monitoring of a large number of transmitters and other emission sources, fixed stations in larger cities are normally sited closer together than in rural areas. For this reason, in planning large new SMNs or in optimizing similar existing SMNs in large cities, the step described under § 3.2.2.2 can begin with the overlying of a territory of the city by a tertiary regular network with distances between stations of 15 km, or even by a fourth-order network with distances between stations of 7.5 km (see § 6.8 of the ITU-R Handbook on Spectrum Monitoring, 2011 edition).

The alternative method for planning small and special local SMNs is described below in § 6. In contrast to the method with regular network, it can require to perform a much more computations, so this method is recommended for planning relatively small SMNs.

3.4.2 SMN planning in mountainous and hilly regions

In mountainous and hilly regions it is possible to significantly increase monitoring coverage by siting antennas of fixed stations at high elevations. Simultaneously, the monitoring coverage in these cases might be much more sensitive to the choice of particular sites. An increased possibility of signal reflection influence should be also taken into account.

All these issues are considered in detail in Annex 2.

4 Planning and optimization of TDOA SMNs

Planning methods for blanket coverage of a large area by TDOA stations (similar to the method concerning regular network for planning AOA stations as presented in § 3 above) have recently been developed. Some additional suggestions on the matter are given in section 4.7.3.2 of the ITU-R Handbook on Spectrum Monitoring (2011 Edition) and in Report ITU-R SM.2211-1.

4.1 Main principles

Section 3.2.2.2 describes methods and principles for locating sites for AoA-based monitoring stations. A similar approach can be used for the location of TDOA monitoring sites. Establishing a grid of TDOA stations in primary, secondary and, where needed, tertiary networks, is effective to optimize RF coverage and emitter location accuracy in the regions of interest.

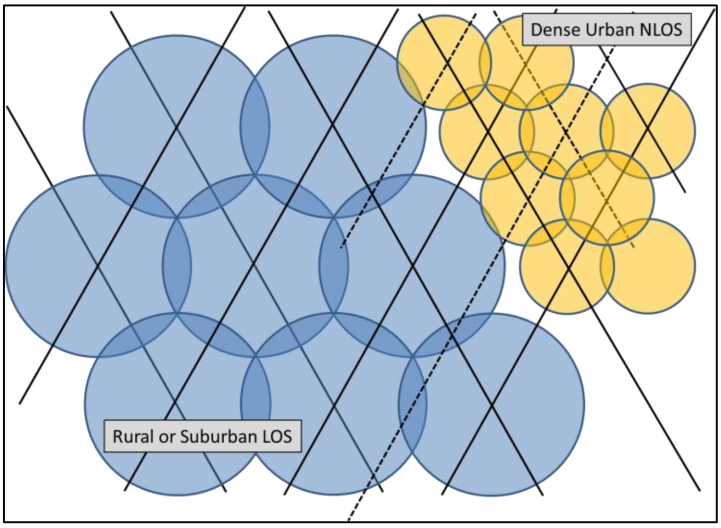
This stated, the primary difference in planning TDOA networks is the relationship between RF detection range and the corresponding geolocation coverage area. This will be discussed in detail. For consistency, the assumption is that blanket coverage of the region is desired.

4.1.1 RF detection range of TDOA monitoring stations

For a TDOA-based SMN, the RF Detection range is used to determine the separation distance of the primary, secondary and tertiary nodes in the monitoring grid. In rural or suburban areas with Line of Sight (LOS), separation between stations can be greater. In dense suburban or urban environments, the separation must be less to achieve RF coverage. These principles hold true for both AOA and TDOA technologies. This is illustrated notionally in Fig. 18.

FIGURE 18

RF detection range in regular primary and secondary networks



Overlap of the RF detection ranges of the monitoring stations creates blanket coverage for the functions of listening and emission characterization as referenced in § 3.1 of this Report.

4.1.2 Geolocation coverage area of TDOA monitoring networks

In TDOA networks, stations can be spaced in such a way as to minimize overlap of the RF detection range and still maintain a large geolocation coverage area that extends to and, in many cases, beyond that of the adjacent monitoring stations. This is due to the cross-correlation gain across spatially-separated TDOA stations. The gain is related to the product of the signal acquisition time (t) and bandwidth (B), or the Time-Bandwidth product. The mathematical expression is:

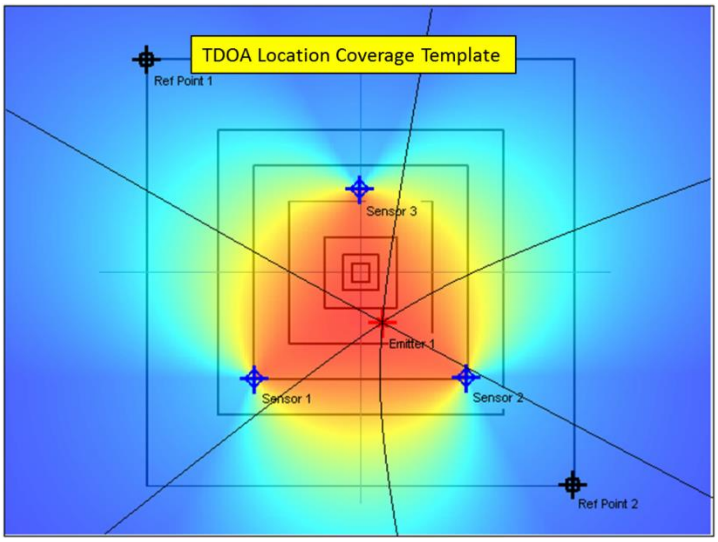
$$10\log_{10}(t \times B)$$

The units are in dB. This processing gain can effectively extend the geolocation coverage area of TDOA networks beyond the limit of each monitoring station's RF detection range.

The Location Coverage Template of a network of three sensors, as defined in § 3.1 and illustrated on in Fig. 4, would be defined best by the network GDOP and more closely represent the boundary of the TDOA monitoring stations as modelled in Fig. 19.

FIGURE 19

LCT for TDOA network resembles GDOP



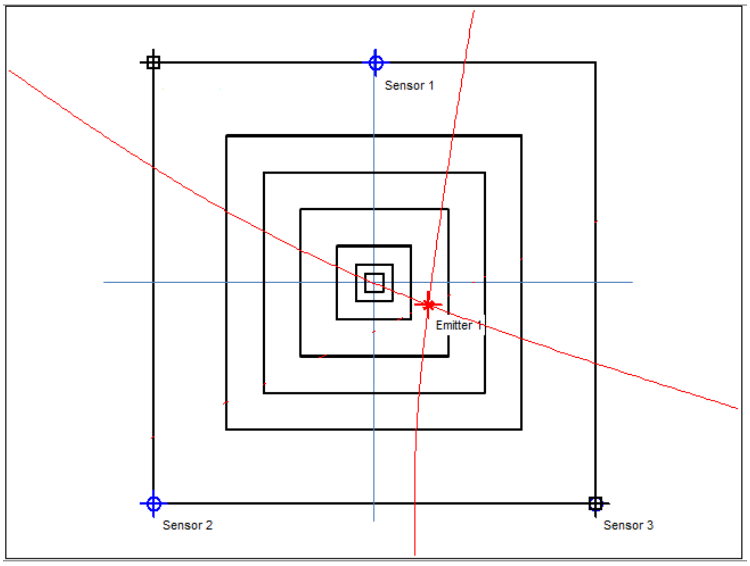
Correlation gain increases as signal bandwidth increases which is very beneficial in urban settings where path loss is greater. In practice, however, the correlation gain cannot be fully exploited since at least one station should be within the RF detection range of the signal in order to characterize the signal and enable better correlation with the other stations. Longer IQ acquisition time may also increase correlation gain if the propagation channel between the emitter and the monitoring stations remains coherent for the duration of the acquisition. However, the channels will not remain coherent for long in dynamic urban environments. For this reason, longer IQ acquisition time may not always be relied upon to extend the geolocation coverage area of TDOA networks in such environments.

4.1.3 Planning for quality location measurements

As stated previously, TDOA networks operate based on the correlation of IQ series data between pairs of monitoring stations. In a network of three TDOA stations, there will be three correlation pairs. At least two station pairs must correlate to determine an emitter location. This is notionally simulated in Fig. 20. In this example, Sensors 1 and 2 correlate producing the near horizontal hyperbolic line (also referred to as isochrones). Sensors 2 and 3 also correlate producing the near vertical red line. Sensors 1 and 3 do not correlate and therefore, produce no isochrones.

FIGURE 20

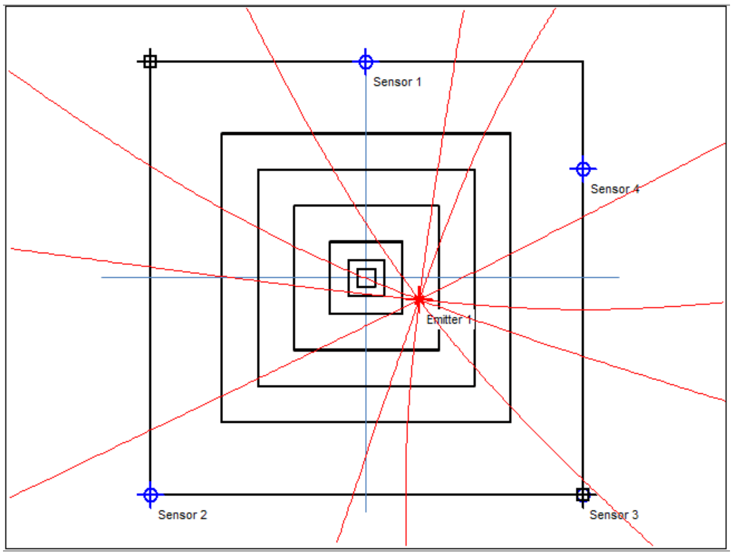
Emitter location by only two correlation pairs in a three-station TDOA network



The addition of a fourth TDOA station doubles the number of possible correlation pairs to six and significantly increases the chance of accurately estimating the emitter location as illustrated in Fig. 21. All six possible correlation pairs are drawn, but only two of the six would be needed to estimate the location.

FIGURE 21

Emitter location by six correlation pairs in a four-station TDOA network



4.2 Planning TDOA SMNs in an Urban Centre

Urban environments present the greatest challenge for planning and optimizing SMNs for good RF coverage and accurate emitter location. Cities are highly dynamic with moving reflectors such as buses, cars, trolleys, and aircraft. Tall buildings act as nearby static reflectors that create a difficult multipath RF environment. Roads and boulevards cut through cities in different patterns based on the concepts employed by city planners – and by expansion and modernization.

This section offers fundamental approaches to planning effective networks of TDOA monitoring sites in urban environments. These guidelines will not eliminate the need for the regular qualifications that go into site selection; but rather are meant to provide an initial approach to planning the network geometry. These supplement the guidance in Report ITU-R SM.2211 Annex 1.

4.2.1 Use of sight lines

Effective urban monitoring networks take advantage of the natural grid created by the system of roads and boulevards in the city. Wide boulevards and major streets create sight lines for RF energy to propagate.

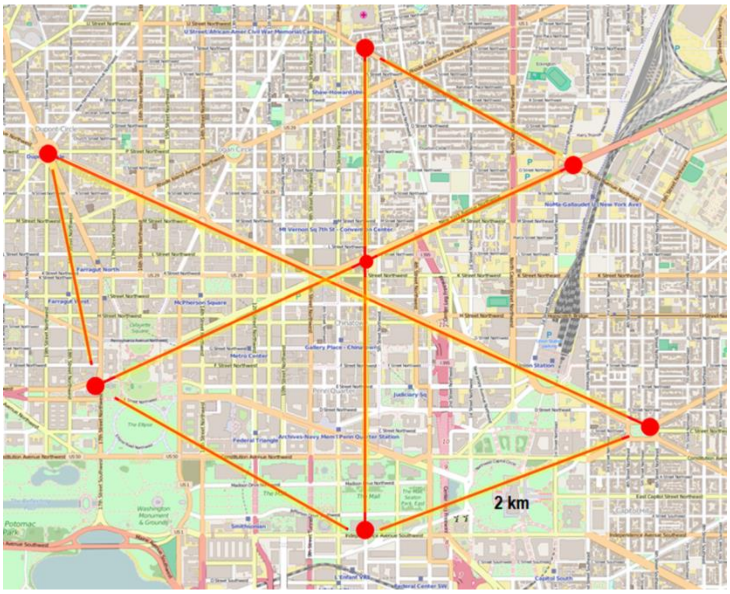
“Within built-up areas, the shadowing effects of buildings and the channelling effects of radio waves along streets make it difficult to predict the median signal strength. Often the strongest paths are not the most obvious or direct ones and the signal strength in streets that are radial to or approximately radial with respect to the direction of the base station often exceeds that in streets which are circumferential.” [6]

This can be used as a guiding principle in planning an effective monitoring network in urban environments. City streets tend to follow one of several patterns that can be used to develop potential locations for monitoring sites. The different patterns shown in Figs 30 and 31 are based on available sight lines in different city plans.

In Fig. 22, the street pattern is a minor orthogonal grid overlaid with a major diagonal grid. The vicinity of the intersections of the diagonal grid may offer good potential sites for monitoring stations (as indicated by the red circles). The geometric pattern of this city provides a template for location of secondary and tertiary monitoring sites that follow a pattern favourable for emitter location using TDOA, RSS and Hybrid (TDOA/RSS) algorithms.

FIGURE 22

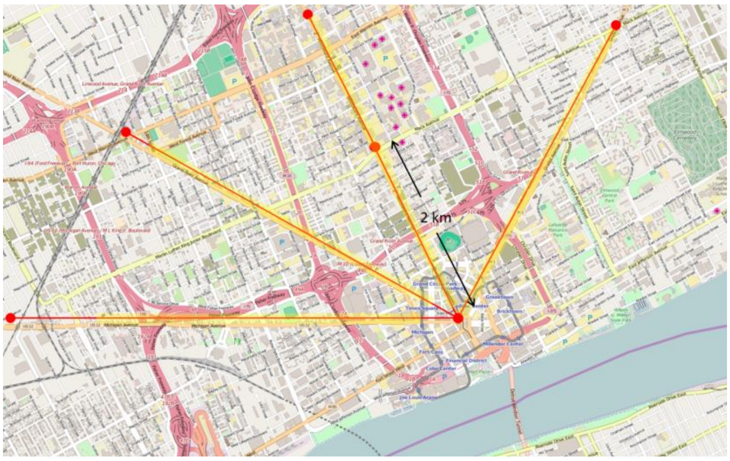
Diagonal site lines in an Urban Centre



In Fig. 23, a city of different geometric pattern representing a minor orthogonal grid overlaid by a radial major grid is seen. Major site lines in this case radiate outwards from an urban centre toward increasingly suburban areas with lower roof lines allowing greater spacing between TDOA monitoring sites.

FIGURE 23

Radial site lines in an Urban Centre



4.2.2 Separation distance between monitoring stations

The system planner must factor in several design goals related to separation distance while laying out a TDOA monitoring network for an urban centre. Additional considerations related to receiver performance are provided in Annex 3.

- Separation distance will affect the overlap of coverage area for different categories of transmitters. Path losses in urban environments are far greater than in other environments in which line of sight is expected.
- For locating narrowband signals, stations spaced too close together may not have adequate baseline for determining Time Difference of Arrival. The combination of timing errors and multi-path effects may prevent a pair of TDOA sensors from correlating.
- As the monitoring network extends out of the dense urban environment into surrounding suburban or industrial areas, separation distances can be increased as line of sight and antenna elevation will result in greater RF detection range of each station.

4.3 Planning TDOA monitoring networks for large rural areas

For rural areas, primary and secondary regular networks should be applied using the guidelines described in § 3.1. The separation distances should be determined with the principles described in this section.

5 Planning of Hybrid monitoring networks

Planning of Hybrid AOA/TDOA monitoring networks is based on the same principles and issues which have been described in §§ 3 and 4 above for AOA and TDOA networks. Significant benefits can be obtained by employing networks of radio monitoring, DF and TDOA systems capable of implementing Hybrid techniques on equipment that meets or exceeds ITU Recommendations for system sensitivity, stability, and accuracy. Compared to networks based on AOA techniques alone or TDOA techniques alone, Hybrid AOA/TDOA networks, in theory, allow coverage of a larger area of interest using a smaller number of stations, and at the same time providing increased geolocation accuracy, inside as well as outside the area surrounded by the spectrum monitoring stations.

5.1 Geolocation method comparisons

It is important to understand the strengths and weaknesses of the different geolocation methods, in order to make informed decisions about which methods are most suitable for a given coverage requirement. A detailed comparison of the AOA, TDOA and Hybrid AOA/TDOA geolocation methods is provided in Report ITU-R SM.2211-1. Included in that Report is a table which summarizes the main characteristics of the three geolocation methods.

5.2 Geolocation coverage and accuracy simulation

Different spectrum monitoring systems (SMS) configurations including AOA, TDOA and Hybrid AOA/TDOA were simulated and compared in terms of their geolocation coverage and accuracy.[2] The analysis was conducted using a software tool that combines geolocation calculation with hearability of the target signal at different stations under consideration, based on transmitter power and signal propagation effects using 3D terrain. The geolocation accuracy was evaluated on the basis of miss-distance. The analysis was conducted under a variety of conditions, such as number of stations involved in the SMN, power of transmitter varied between 1 Watt and 100 Watts, different propagation conditions and different geolocation techniques. The assumptions regarding coverage area include desired coverage both inside the area bounded by the stations, as well as outside the area bounded by the stations.

Based on the coverage requirements and the operating conditions simulated (in Report ITU-R SM.2211-1), the use of Hybrid AOA/TDOA techniques provided better accuracy over a larger coverage area for both three and four station cases. Illustrated in Fig. 24 is another example case, of six stations with a 10 Watt emitter. A system consisting of AOA stations covers the entire area of interest, but geolocation accuracy is poor for distant transmitters. A system consisting of TDOA stations provides good accuracy in the area within the TDOA sites, but geolocation accuracy degrades rapidly outside this area. In the example simulated, a Hybrid AOA/TDOA network leverages the advantages of wider area coverage of AOA stations (for a given number of stations) with the less complex equipment/antenna advantages of a TDOA station.

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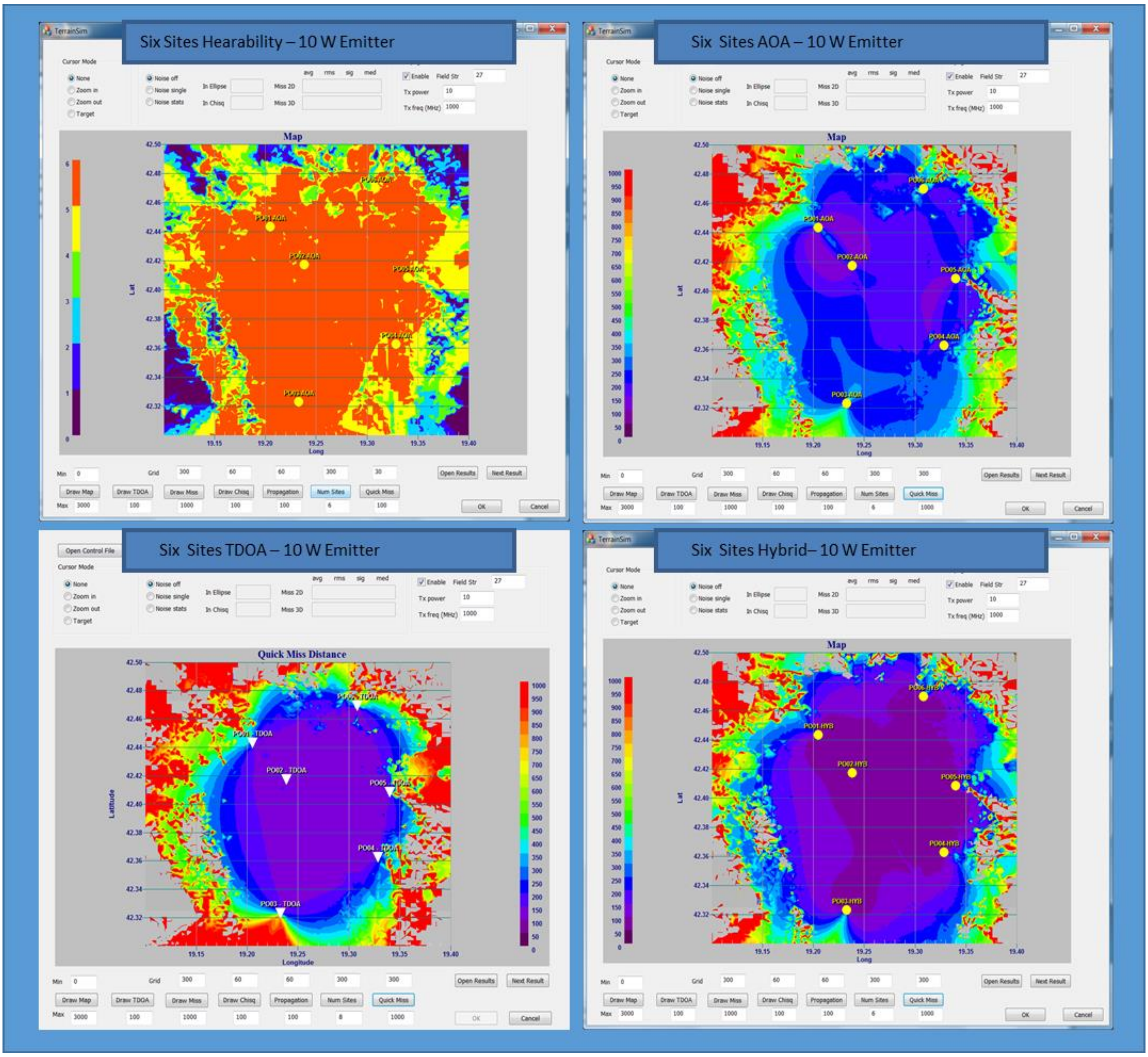
[2] The propagation model used for this simulation is TIREM – the Terrain Integrated Rough Earth Model for propagation (see ITU-R Handbook on National Spectrum Management).

FIGURE 24

Six-station coverage example, showing 10W hearability and coverage of AOA, TDOA and Hybrid systems



5.3 Summary of Hybrid system performance

A Hybrid AOA/TDOA geolocation solution is expected to require fewer stations than a TDOA only geolocation solution to achieve the same or better coverage and the same or better accuracy, for many commonly encountered wide-area coverage requirements. The Hybrid solution combines the benefits of AOA systems (better performance with narrowband signals, wide area coverage, etc.) with the benefits of TDOA systems (simpler installation and antenna requirements, rejection of uncorrelated noise, etc.).[3] Therefore, in some cases, a Hybrid AOA/TDOA network may offer a lower installation cost and lower recurring cost for a given coverage area over the life of the network.

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[3] A more complete description can be found in § 3 of Report ITU-R SM.2211-1.

6 Generalized method for planning small and special local SMNs

When you are planning network of monitoring stations first of all you should decide what tasks will be solved by this network. Since for listening and/or measuring characteristics of radio signals in some cases one monitoring station can be sufficient, unlike to AOA network (minimum – 2 stations) or TDOA network (minimum – 3 stations). Coverage area of monitoring stations in each of these cases is defined by the value of required minimum field strength.

Therefore, if it is assumed that the future SMN have to solve several tasks, the planning of the network should begin with the solution of the task with the highest required minimum field strength, and then, in the order of its reduction:

1) direction finding and estimation of emitter location (20 dB(µV/m)) in accordance with the ITU-R Handbook on Spectrum Monitoring);
2) measuring parameters of radio signal (12 dB(µV/m)) in accordance with the ITU-R Handbook on Spectrum Monitoring);
3) listening spectrum (0 dB(µV/m)) in accordance with the ITU-R Handbook on Spectrum Monitoring).

This sequence of actions will allow covering survey area with the smallest number of monitoring stations and preventing from unnecessary financial losses.

At the preparatory stage all decisions mentioned in § 2 above should be solved, including defining the territory to be monitored, choosing a method for calculation of radiowave propagation, determination of maximum possible value of emitter location uncertainty (for AOA/TDOA planning), calculating the boundary value of minimum field strength, identifying areas within which it is not recommended to place monitoring stations, etc.

The following terms and definitions are used in the method described below:

“AOA-link” – two monitoring stations which can be used for determination of emitter’s location with predefined location uncertainty in AOA SMNs.

“TDOA-link” – three monitoring stations which can be used for determination of emitter’s location with predefined location uncertainty in TDOA SMNs.

“covered” test transmitter – test transmitter whose field strength at the site of monitoring station is greater threshold value (required minimum field strength) and whose positioning error (emitter’s location spotted by AOA/TDOA monitoring stations) does not exceed the predefined value of maximum location uncertainty.

rating of site for monitoring station – the number of test transmitters lying in study area that can be covered by monitoring station installed within this site;

rating of “AOA-link” – the number of test transmitters lying in study area that can be covered by this “AOA-link”;

rating of “TDOA-link” – the number of test transmitters lying in study area that can be covered by this “TDOA-link”.

6.1 Computer-aided modelling of small and special local SMNs

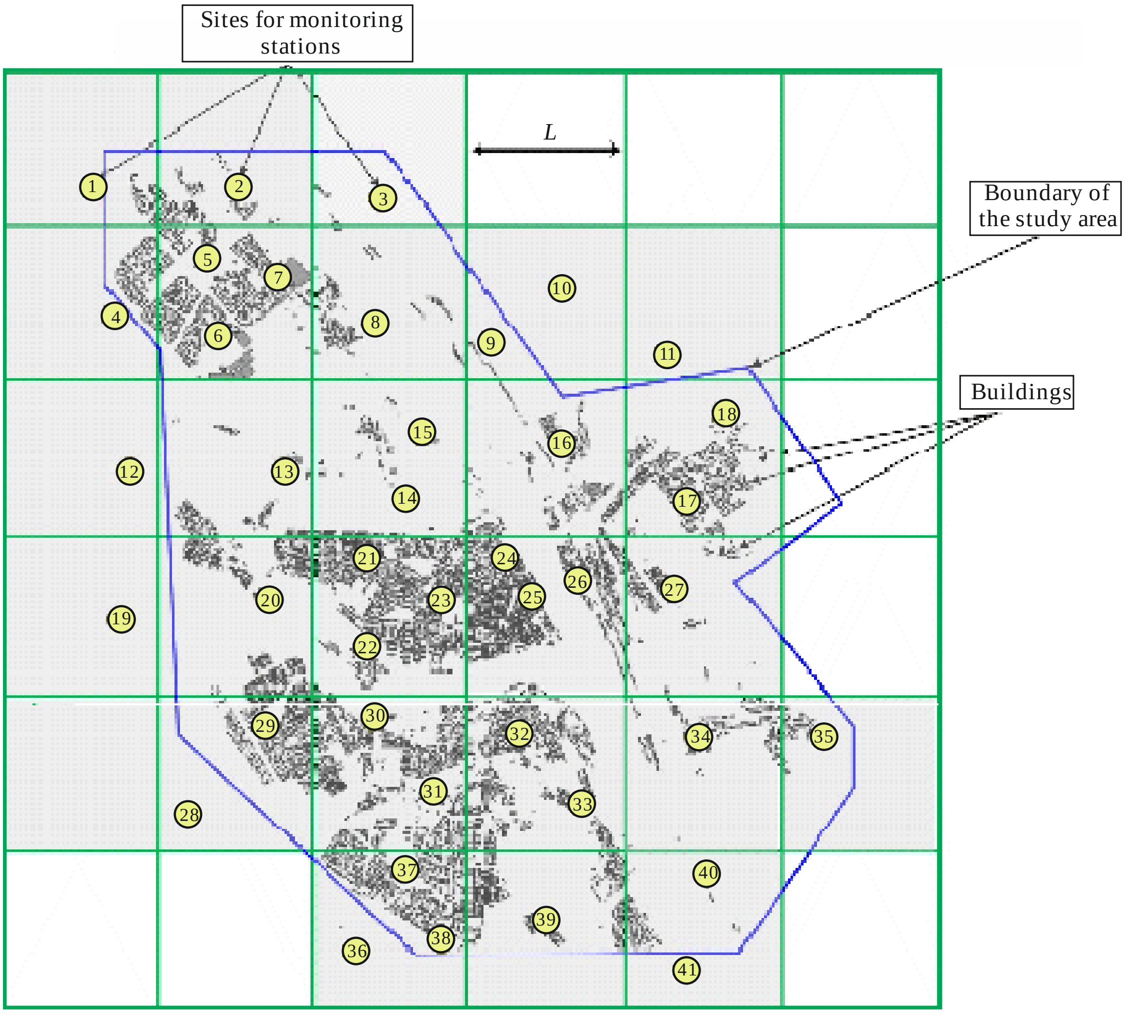
Step 1: The selection of possible sites for radio monitoring stations

After determining the territory that needs to be monitored, choose sites for future radio monitoring stations. For this purpose a grid with step $L = 0.5…5$ km is applied so that it covers the study area and also neighboring areas. The smaller step of grid is better, but it highly depends on available computational resources.

In each cell of the grid select at least one site that potentially may be used for placing of radio monitoring station (there may be selected several sites in some cells). For example, in urban areas it can be roof of high building, but in rural areas it can be the high place near road or the place with necessary infrastructure (see Fig. 25).

FIGURE 25

Selection of possible sites for radio monitoring stations



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Step 2: The imposition of "computational grid"

Overlay "computational grid" within boundaries of the area that should be covered by radio monitoring. The step of "computational grid" must be not big in comparison with other external objects. For example for planning of SMNs in urban areas the step of "computational grid" may be equal 5…50 m. Test transmitters are placed in the nodes of this grid. e.i.r.p., median height and other characteristics of test transmitters shall correspond to the characteristics of real radio stations, which are supposed to be under control (see Fig. 26).

FIGURE 26

The imposition of “computational grid” (in case of outdoor emitters)

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Step 3: Performing calculations

Calculate the service area for all chosen sites. If study area is partly covered by existing monitoring network which will be upgraded then all further calculations are made taking into account the coverage of these stations with their upgraded characteristics. The coverage area of each monitoring station is defined by the following conditions:

- maximum distance (R_{max_loc}) from each monitoring station to some test transmitter is defined by the formula (only for planning AOA SMNs, see Fig. 27):

  R_{max} = maximum location uncertainty (Δ_{Err}) / tangent (uncertainty on bearing (θ°));
- the calculated field strength in chosen sites of monitoring stations must be greater than the minimum required field strength (see Fig. 28).

FIGURE 27

Example for definition of maximum distance from monitoring station to test transmitter (only for planning AOA SMNs)

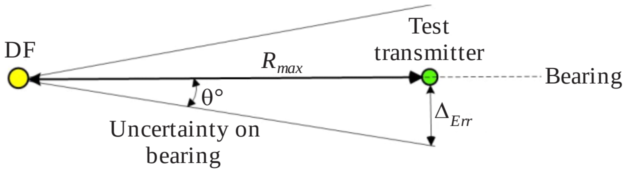

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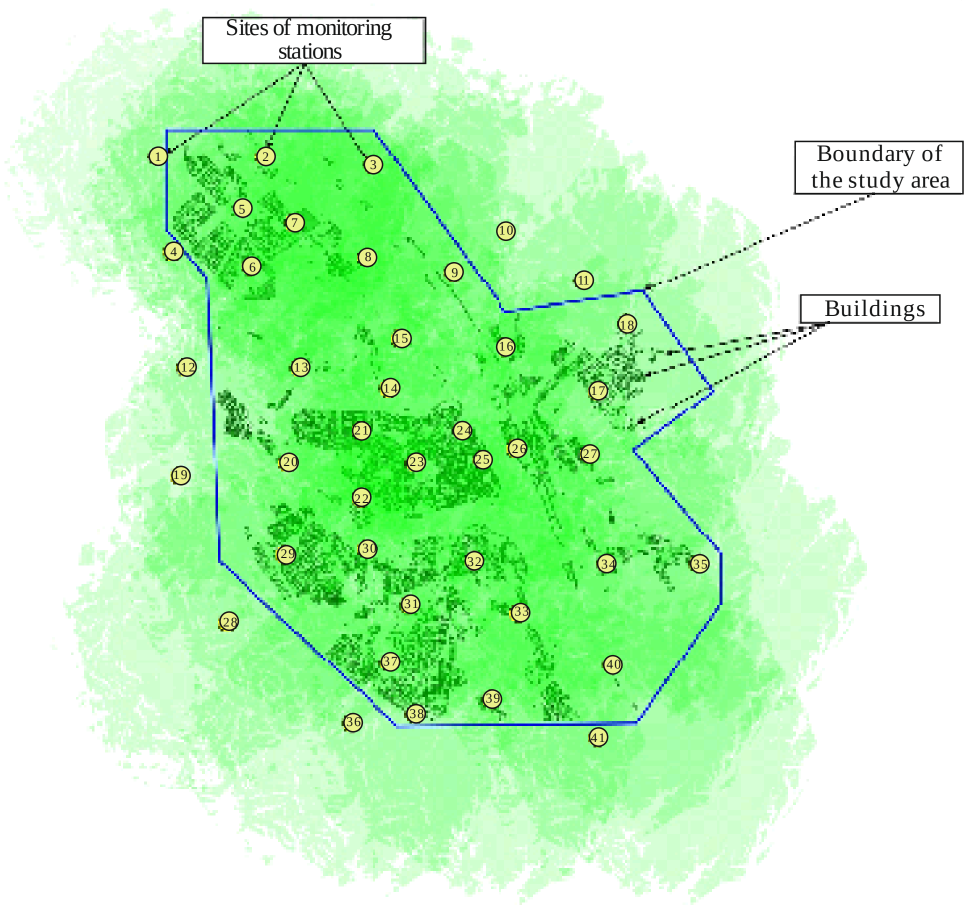
FIGURE 28

The coverage zones of chosen sites for monitoring stations



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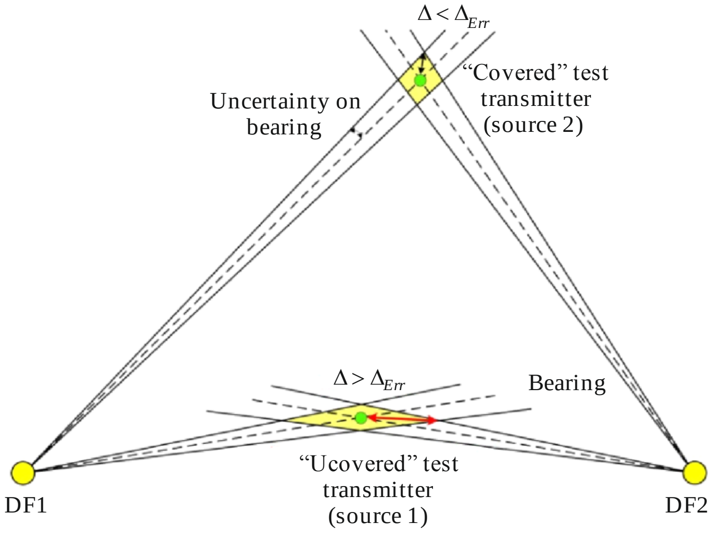
Step 4: Making diagram of "AOA/TDOA-links" and selecting the reference of monitoring stations

Planning AOA SMNs

For planning AOA SMNs it is necessary that each test transmitter shall be covered by at least two monitoring stations. So for each pair of monitoring stations, their common coverage zone is determined by area within which location uncertainty will not exceed predefined value of maximum location uncertainty ((Δ_{Err}), see Fig. 29).

FIGURE 29

Example for determination of coverage zone by two AOA stations



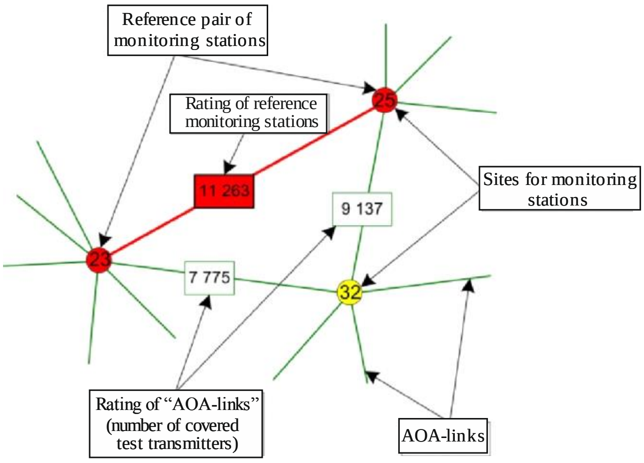
Report SM.2356-22

The rating of this so-called "AOA-link" (pair of monitoring stations) is equal number of covered test transmitters lying within this zone. After calculation the ratings for all "AOA-links" it is possible to make diagram of "AOA-links".

Among all pairs of AOA-stations you have to choose the pair of monitoring stations with the highest rating (with the larger coverage zone in study area). If necessary, the sites for future monitoring stations are additionally examined. The resulting first pair of monitoring stations is considered as "reference pair" (Fig. 30).

FIGURE 30

The part of diagram of "AOA -links"



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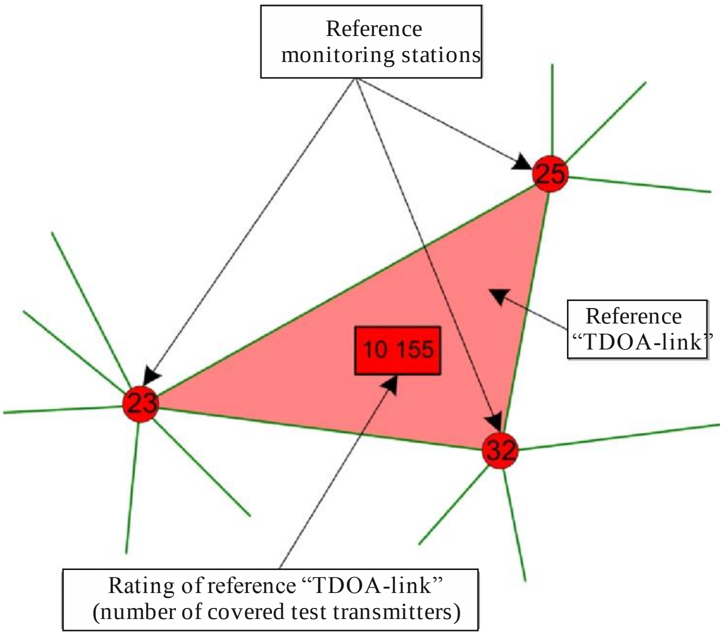
Planning TDOA SMNs

A similar procedure is carried out for planning TDOA stations. But in this case there is one exception: it is necessary that each test transmitter should be covered by at least three monitoring stations (Fig. 31).

FIGURE 31

The part of diagram of "TDOA -links"



Report SM.2356-24

Planning SMNs for listening and measuring parameters of radio signal

In case of planning SMNs for listening and measuring parameters of radio signal you have to choose the station with the largest coverage zone in study area (with the highest rating). If necessary, the site for future station is also additionally examined.

Step 5: Definition of uncovered area

After specifying the locations for radio monitoring stations, their coverage areas are "subtracted" from the study area. It should be noted that after this iteration ratings of remaining sites for monitoring stations or ratings of remaining "AOA/TDOA-links" will change.

Step 6: Site selection for new monitoring stations

Uncovered region in study area is analyzed. Answers to the following questions should be obtained: Can it be covered by mobile stations? Is there a need for planning of additional fixed monitoring stations? If such a need exists, then you have to choose the next site(-s) for monitoring station(-s) with the highest rating for uncovered region of study area.

Planning AOA SMNs

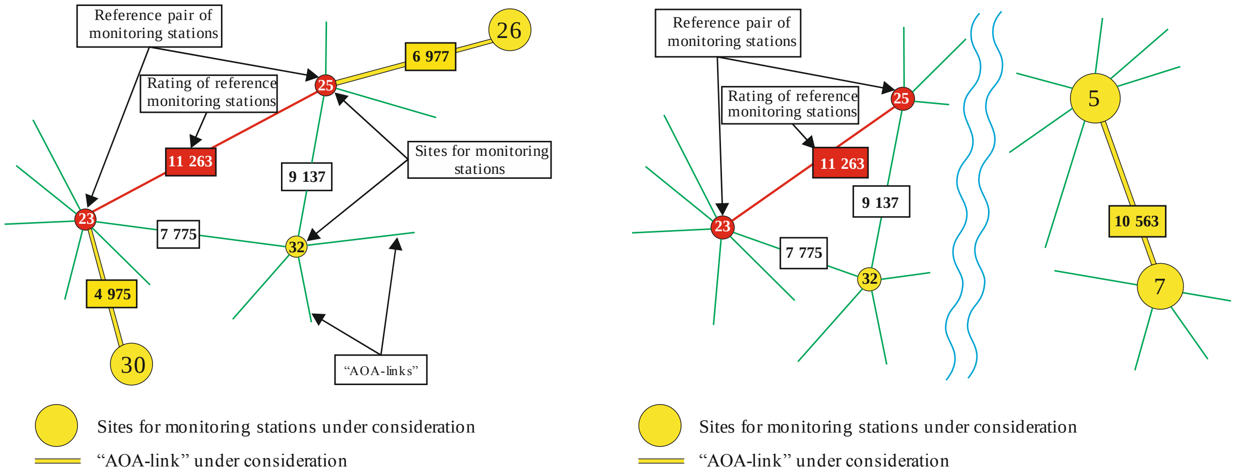
In case of planning AOA SMNs it would be the next pair of stations with highest rating. If this pair is not adjacent to the "reference pair", it should be determined whether to increase the chain of "reference pair" up to four stations, so that the summarized rating of such chain will be more than the total rating of the two considered isolated "AOA-links". Choose the variant with the highest total rating (see Fig. 32). It should be noted that:

$$\text{Rating } (S_{30\text{-}23} - S_{23\text{-}25} - S_{25\text{-}26}) = \text{Rating } (S_{30\text{-}23} \cup S_{23\text{-}25} \cup S_{25\text{-}26});$$

$$\text{Rating } (S_{30\text{-}23} - S_{23\text{-}25} - S_{25\text{-}26}) \neq \text{Rating } (S_{30\text{-}23}) + \text{Rating } (S_{23\text{-}25}) + \text{Rating } (S_{25\text{-}26}).$$

FIGURE 32

Example of sites selection for monitoring stations (the part of diagram of "AOA -links")



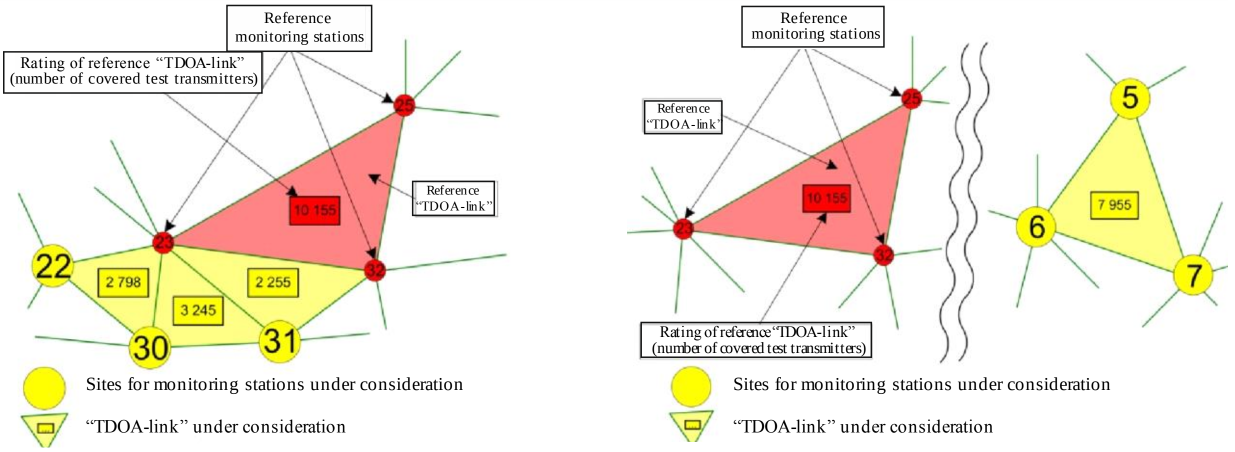
Report SM.2356-25

Planning TDOA SMNs

A similar procedure is carried out for planning TDOA stations. It would be the next "TDOA-link" with the highest rating. If these stations are not adjacent to the "reference stations", it should be determined whether to increase the chain of "reference stations", so that the summarized rating of such chain will be more than the total rating of the two considered isolated "TDOA-links". Choose the variant with the highest total rating (Fig. 33).

FIGURE 33

Example of sites selection for monitoring stations (the part of diagram of "TDOA -links")



Report SM.2356-26

Planning SMNs for listening and measuring parameters of radio signal

In case of planning SMNs for listening and measuring parameters of radio signal, analyze the uncovered study area and then select the next station with the highest rating (with the largest coverage zone in uncovered study area).

Step 7: Making new iterations

If necessary, repeat steps 5, 6 and step 7.

7 Conclusion

The process of planning new SMNs and optimizing existing SMNs in terms of monitoring coverage is a rather complex undertaking and it requires certain administrative decisions to be taken at various stages. The process may also be rather long drawn-out, especially when it comes to acquiring the necessary land for siting fixed stations, as each potential site has to be surveyed for suitability and coverage. It might be necessary to repeat the procedure in order to find sites that are available and meet all the requirements to the greatest extent possible.

Calculations of monitoring coverage are required at virtually every stage of planning and optimizing an SMN. They thus play a crucial role in the process, as it is clear from Recommendation ITU-R SM.1392-2. This is especially true of LCT calculations, as it is precisely this parameter, as we have seen, that is the best indicator of quality of the SMN as a whole and of its individual parts.

Annex 1

Practical example on local AOA SMN planning at relatively plain terrain

A1-1 Introduction

The operating efficiency of any national spectrum monitoring service depends on some factors, the main factors of them are:

- the SMN structure;
- the number of spectrum monitoring stations and radio monitoring equipment used and their technical capacities.

The SMN structure is determined by spectrum monitoring service tasks, working frequency band and distribution of radio transmitters within the spectrum monitoring service responsibility area.

In most cases the frequency band of fixed SMNs operation is limited to a maximum 3 000 MHz and the frequency band of fixed direction finding networks operation is limited to a maximum 1 000 MHz.

Aggregated coverage area of SMN is formed by consolidation of all fixed monitoring stations coverage zones.

Aggregated direction finding area of direction finding network or direction finders cluster is formed by aggregating the direction finding areas of all direction finders, in the network.

Aggregated location area is formed by the intersection area of direction finding areas of a minimum of two fixed direction finders.

The coverage zone of a single fixed monitoring station and direction finding area of single direction finder may be calculated using the method in the latest version of Recommendation ITU-R P.1546 or free space condition or may be measured in practice.

Initial data are required for purposes of comparing the direction-finding coverage zones boundary are typical sensitivity value (field-strength threshold value) of direction finder receivers and monitoring stations receivers for different operation modes, typical transmitter output power, typical monitoring station antenna height and transmitter antenna height is determined in ITU-R Spectrum Monitoring Handbook.

A1-2 Initial data for planning the SMN topology

In practice two main approaches on the planning of fixed SMN may be used:

- to cover the greatest possible land area using the smallest possible number of fixed monitoring stations;
- to cover by monitoring the greatest number of radio transmitters using smallest possible number of fixed monitoring stations.

First approach is described in section 6.8 of the ITU-R Spectrum Monitoring Handbook (2011 edition) and it is based on usage of a regular structure of direction finders network in which direction finders are located on vertexes of regular triangles. But this method does not provide the minimum number of direction finders (or fixed monitoring stations). In the calculation of direction finding area for optimization of SMN efficiency the terrain may be taken into account.

Second approach performs preliminary simulations of different varieties of fixed SMN topology. In this case of spectrum monitoring system topology planning it is necessary to take into account three main factors:

- the distribution of radio transmitters on responsibility area;
- conditions of radiowave propagation in different frequency bands;
- multiplexing method which is used in certain telecommunication technologies.

Multiplexing method determines the potential of direction finding network to locate radio transmitters.

A1-3 Optimization of simplest SMN topology

The simplest direction finding network consists of two direction finders, which are located at a distance of about 8-10 km between each other. Unfortunately such structure may have “blind” zones, i.e. areas in which direction finding network cannot locate radio transmitters with required accuracy or does not provide their location at all.

For example two possible varieties of location of two direction finders in Lvov (Ukraine) are displayed in Fig. A1-1. The location of UHF radio transmitters which operate in the 400 MHz frequency band are labeled with green and pink icons, and the direction finders sites are labeled with small black triangles. The borders of direction finding areas calculated for using free space condition are marked with a red line, the aggregated location area is marked with a blue line.

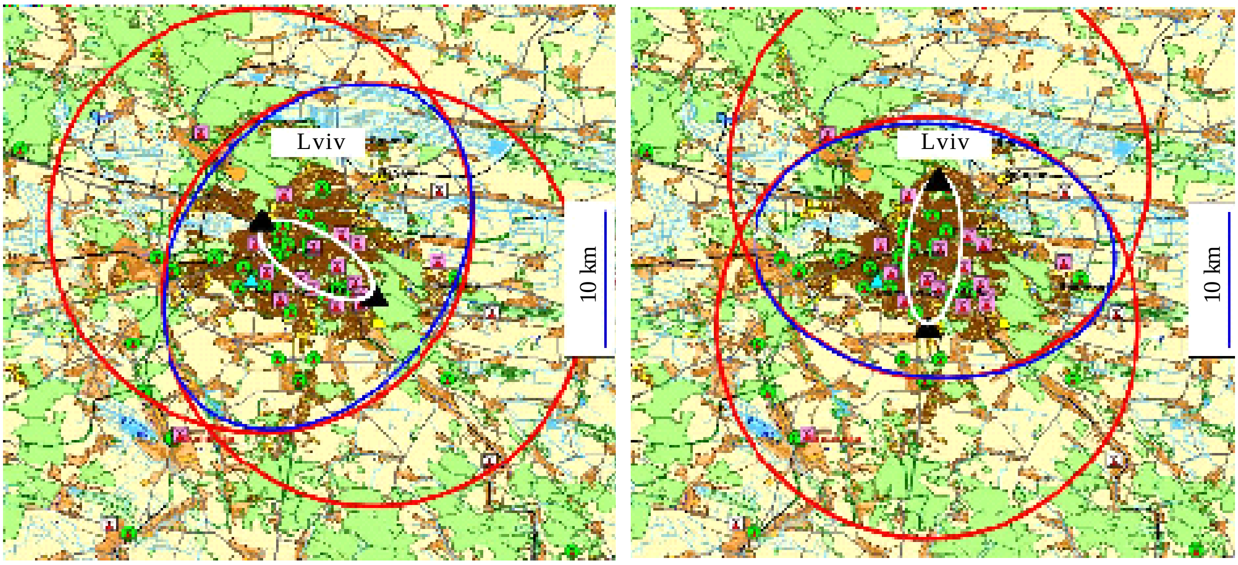
If two direction finders are located on opposite sides of the settlement then the aggregated location area covers some of the transmitters with others falling within the “blind” zone (its border is marked with white line in Fig. A1-1). In this case the number is about 30% of total number of transmitters.

In practice there are two solutions for eliminating the “blind” zone:

- to use third direction finder;
- to optimize direction finders location.

FIGURE A1-1

Possible location varieties of two direction finders



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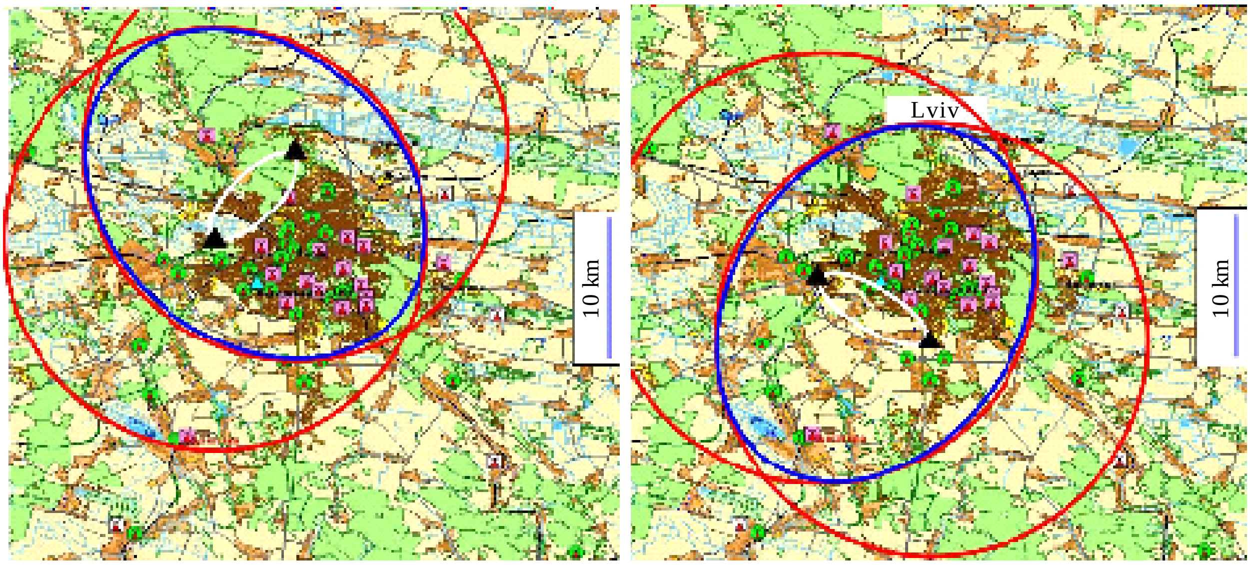
The last solution is based on usage two direction finders only. Some variants of possible direction finders location is displayed in Fig. A1-2. In this case aggregated location area covers all transmitters with no transmitters in the "blind" zone.

FIGURE A1-2

Alternative varieties of location two direction finders in Lvov



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The topology of the simplest location network which consists of two direction finders is the most optimal one if they are disposed on distance about 8-10 km between each other near the outskirt of town. Such direction finders disposition provides to minimize the number of radio transmitters which may be fall into "blind" zone.

A1-4 Regular topology of large SMN

To provide the spectrum monitoring and location of radio transmitters in a large territory it is necessary to use many direction finders.

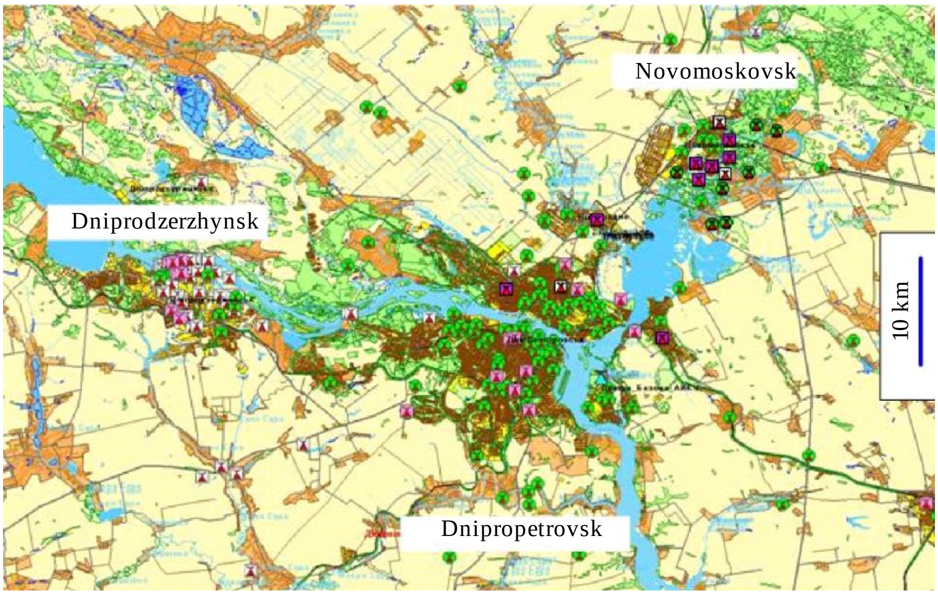
Figure A1-3 displays the distribution of radio transmitters (TRUNK base stations and UHF transmitters) in 400 MHz frequency band on Dnipropetrovsk and its satellite towns – Dniprodzerzhinsk and Novomoskovsk (Ukraine). The locations of transmitters are labeled with green and pink icons.

Figures A1-4 and A1-5 display two possible varieties of calculated topology of hypothetical direction finding and location network which cover transmitters on mentioned territory and are based on regular network structure.

The network in Fig. A1-4 includes eight direction finders and it covers 100% of the area of interest and provides detection and measurement of frequency parameters about 99% transmitters but it provides the location of less than 87% radio transmitters.

FIGURE A1-3

Distribution of TRUNK base stations and UHF transmitters in frequency band 400 MHz



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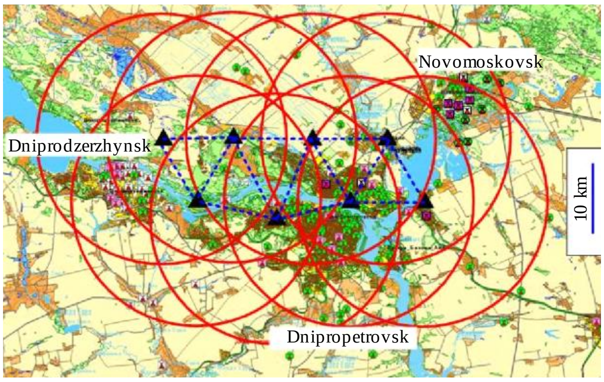
The network displayed in Fig. A1-5 covers 100% of the area of interest and provides detection, measurement of frequency parameters and location about 99% radio transmitters. But it requires a minimum of seven direction finders.

FIGURE A1-4

Hypothetical regular direction finding and location network (Var. 1)



Report SM.2356-A1-04

FIGURE A1-5

Hypothetical regular direction finding and location network (Var. 2)

Report SM.2356-A1-05

A1-5 Irregular structure of SMN topology

The topology of a large direction finder networks is based on irregular structure and is determined “step by step” based on two criterions:

- to cover by monitoring the greatest number of radio transmitters using smallest possible number of fixed monitoring stations;
- to minimize the number of radio transmitters in the “blind” zone between two nearest located direction finders.

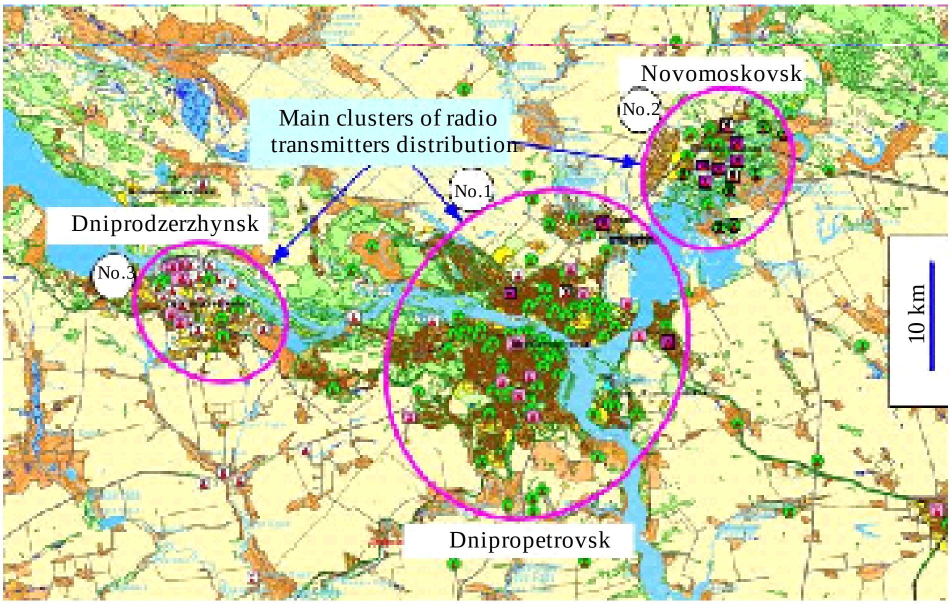
Step 1. The distribution of radio transmitters in the area of interest in the frequency band is determined. The distribution of radio transmitters in VHF/UHF bands on territory of Dnipropetrovsk and its satellite towns – Dniprodzerzhinsk and Novomoskovsk is displayed in Fig. A1-3.

Step 2. Large clusters of radio transmitters in area of interest is determined.

In Fig. A1-6 three big clusters of TRUNK base stations and VHF radio transmitters in frequency band 400 MHz are bounded by pink ellipses.

FIGURE A1-6

Main clusters of transmitters in frequency band 400 MHz



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Step 3. The preliminary topology of spectrum monitoring system is simulated.

The topology of SMN is determined using an iterative procedure. The first and obvious proposal is to form the location area for cluster #1 by deploying two direction finders (Fig. A1-7).

FIGURE A1-7

Primary variation of SMN topology

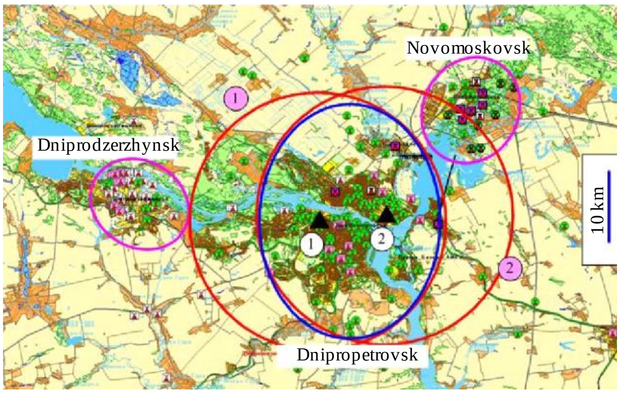

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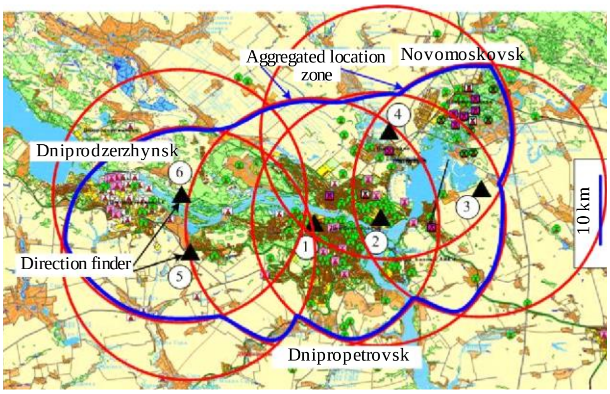
FIGURE A1-8

Aggregated location area of SMN



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But in this case to determine the location of transmitters into clusters #2 and #3 it is necessary to deploy two additional direction finders pairs (Fig. A1-8). The aggregated location area for this SMN is marked by a blue line.

Step 4. Optimization of SMN topology.

Using the irregular structure it is possible to minimize the number of direction finders and to optimize the SMN topology as well.

At the first stage of the location network modelling three direction finders (1, 2 and 3) are located to create the location area on #2 cluster of transmitters and most part of #3 cluster of transmitters (Fig. A1-9).

At the second stage the location area is extended by introduction of direction finders 4 and 5 (Fig. A1-10). The aggregated location area is displayed by a blue line.

FIGURE A1-9

1-st step on modelling of irregular topology of SMN

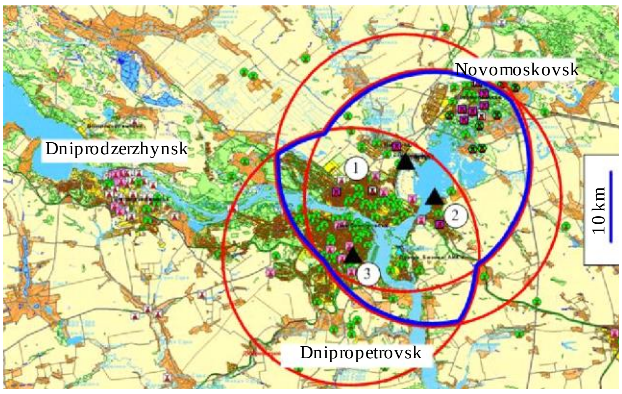

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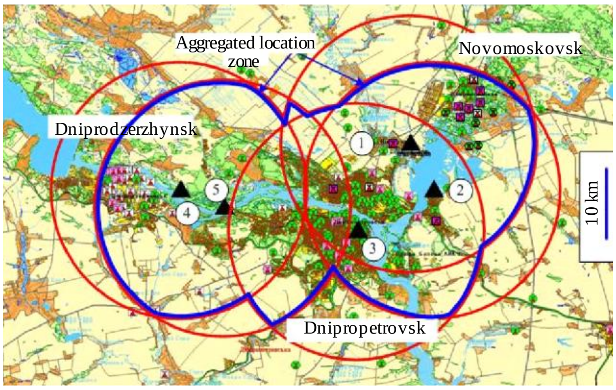
FIGURE A1-10

2-nd step on modelling of irregular topology of SMN



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To form the predetermined coverage area some direction finders may be added using the above described criterion.

The topology of this local direction finding and location subnetwork in Dnipropetrovsk, Dniprodzerzhinsk and Novomoskovsk was determined based on simulated results. The subnetwork includes five direction finders and it covers about 100% of VHF radio transmitters and about 99% of appreciable area. Also there is not any “blind” zone into this local subnetwork, including possible “blind” zone between fixed direction finders 4 and 5.

During the planning the irregular structure of the direction finding and location network topology can be optimized to cover more radio transmitters using the smallest possible number of fixed direction finders.

Annex 2

AOA SMN planning in mountainous and hilly regions

A2-1 Preface

It is a well-known fact that the coverage zones of monitoring stations increase with antenna height. However, any significant increase in the physical height of the antenna mast is fraught with technical difficulties and considerable financial cost. In practice therefore, the effective height of a station's antenna is usually increased by siting it on higher ground. In countries with mountainous regions, effective antenna heights can sometimes be increased up to 3 000 m, a figure cited in Recommendation ITU-R P.1546-4.

The general methodology that has been developed recently [1, 2] and the corresponding software for SMN planning (described in Annex 5 of the ITU-R Handbook on Computer-Aided Techniques for Spectrum Management (CAT), edition 2015) enable us to undertake quantitative assessments of the likely benefits of siting fixed station antennas in this way, analyse associated phenomena and formulate appropriate Recommendations [3].

Monitoring coverage calculations were based on the methodology set out in sections 4.7.3.1.4 and 6.8 of the ITU-R Handbook on Spectrum Monitoring (edition 2011). The test transmitter used for these estimates was a 10 W private mobile radio (PMR) operating at 900 MHz, with an antenna height of 6 m above the ground. This corresponds to a 3 m antenna mast sited on the roof of a single-storey building, and gives us a useful model of a small mobile radio base station with minimal parameters. The radiowave propagation model used is based on the methodology set out in Recommendation ITU-R P.1546-4 Annex 5, of which § 1.1 describes a recommended method of calculation applicable to monitoring. DF uncertainty for all the fixed stations under consideration is taken to be 1° r.m.s., and 2° r.m.s. for mobile stations.

A2-2 DF and location coverage zones for station antennas sited at higher altitudes

In seeking to increase the effective height of a station's antenna, we must not forget that the station needs an appropriate infrastructure in order to function, above all an electrical power supply and access road, which is needed even in the case of an unattended automated station in order to allow maintenance etc.

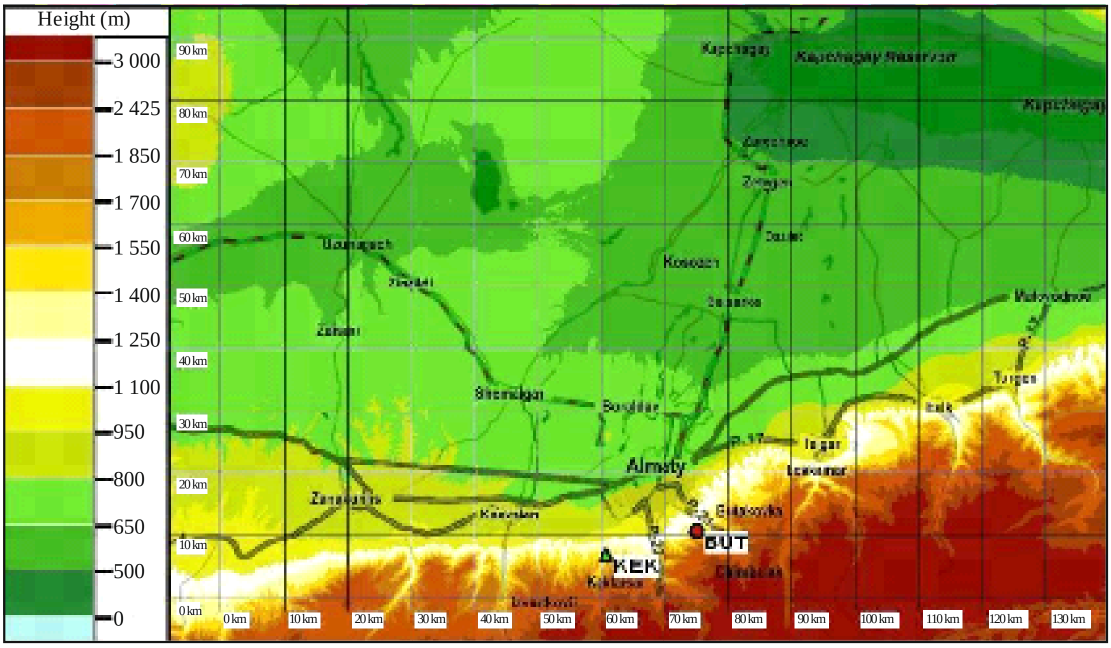
In practice therefore, the siting of stations and their antennas in mountainous areas is restricted to within the upper boundary of the habitable zone where such infrastructure already exists.

Two virtual fixed stations with antennas located in the foothills south of Almaty (Republic of Kazakhstan) [3]. This situation is shown in Fig. A2-1, which shows the topography of the area in question. The antenna of one of the stations (KEK) is sited at a height of 1 506 m, the other (BUT) at 1 568 m. The physical height of the antenna masts is assumed to be 10 m, as in these circumstances an antenna's physical height has virtually no effect on its effective height as determined in accordance with the procedure of Recommendation ITU-R R.1546-4. A lower antenna mast height is not recommended for reasons of safety. Specific siting points of antennas have been carefully selected in order to maximize monitoring coverage (see below).

Figure A2-2 shows the location coverage template (LCT) of both stations.

FIGURE A2-1

Siting of virtual stations and topography of the region under consideration



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It is clear from Fig. A2-2 that siting the station antennas in this way enables us to carry out monitoring at very great distances within the boundaries of the plain adjacent to the mountain range, especially towards the north and west of Almaty (up to 70 km or even further). It is also clear from Fig. A2-2 that with the station antennas thus sited, the southern part of Almaty is covered with a location uncertainty (LU) of between 200 and 400 m, and the northern part with an LU of between 400 and 600 m. This considerably speeds up the process of homing a transmitter (or any other sources of emissions) with a mobile station, where is necessary. On the other hand, near the outer boundaries of the LCT at distances of around 60 to 70 km from Almaty, LU values are very high (around 12 to 14 km). The LU in this example thus varies by a factor of 70 within the LCT. This phenomenon should be taken into account while homing activities.

Figure A2-2 shows that siting station antennas at higher altitudes is very effective and enables us to cover very large areas using a small number of fixed stations. This does, however, require somewhat greater care in selecting antenna sites. On a plain, moving antennas a few hundred metres or even a few kilometers has little impact on the overall monitoring coverage zones of a group of stations in the SMN . In mountainous terrain, on the other hand, moving antenna sites by even a few tens of metres can significantly reduce the monitoring coverage zones of the stations concerned. This can also adversely affect the overall location coverage zone if there are few fixed stations in the SMN. Figure A2-3 shows the LCT that results when the station BUT is moved only 100 m to the south (site B2). When compared with Fig. A2-2, the adverse consequences of such a move are clear.

For that reason, once computer modeling of the monitoring network in such mountainous terrain has been done, it is essential to carry out a careful survey of potential sites, involving a thorough visual survey (using binoculars) of the area with regard to any possible obstacles to radiowave propagation in the direction of the territory to be monitored.

A2-3 Reducing the likelihood of reflection effects

Another factor, and one very typical of mountainous areas, is the phenomenon of reflections from nearby mountains [4]. This requires particular attention in the process of selecting sites for station antennas. They should be sited on mountain ridges that project out into the monitored territory. This will reduce the likelihood of reflections from nearby ranges of the same or greater height. Reflection effects from lower mountains are somewhat less likely.

Figure A2-4 shows just such an approach to selecting sites for antennas associated with the stations KEK and BUT. If on the other hand a station antenna is sited set back between projecting ridges of the same or greater height, as is the case with station N in Fig. A2-4, the likelihood of interference from reflections is considerably greater. Figure A2-4 shows the high probability of reflections of a signal received by the antenna of station N from transmitter T_r.

FIGURE A2-2

DF and location coverage with appropriate siting of stations KEK and BUT

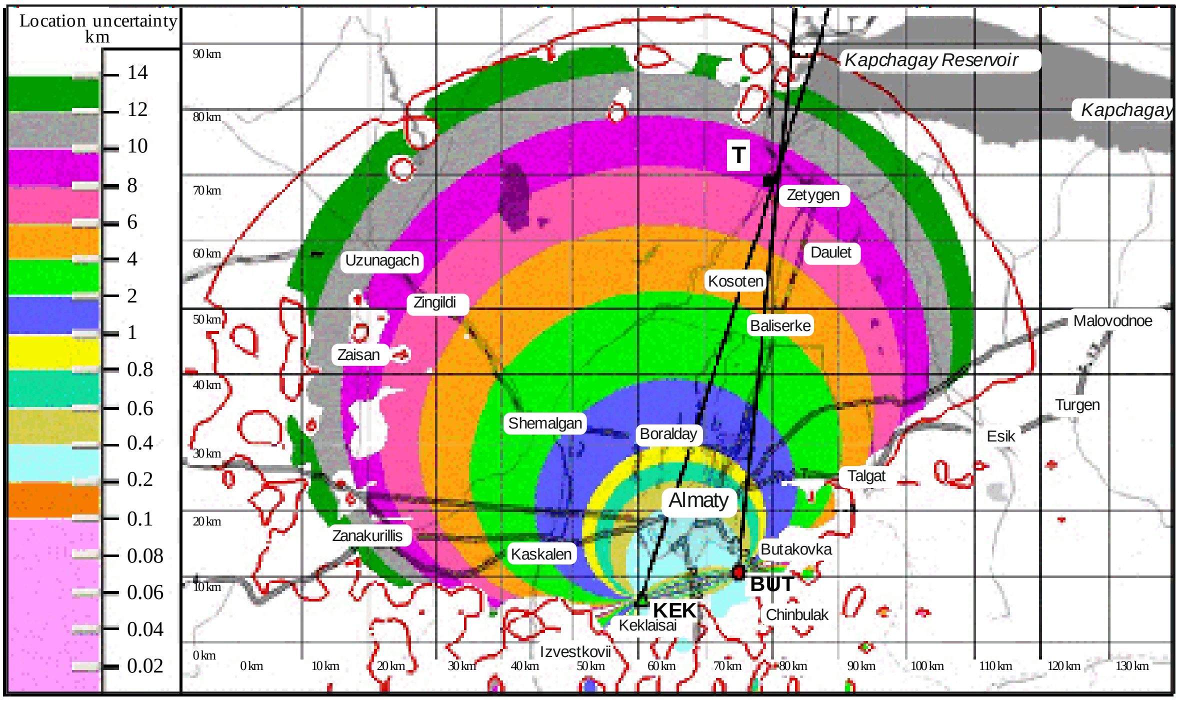

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FIGURE A2-3

DF and location coverage with inappropriate siting of station BUT

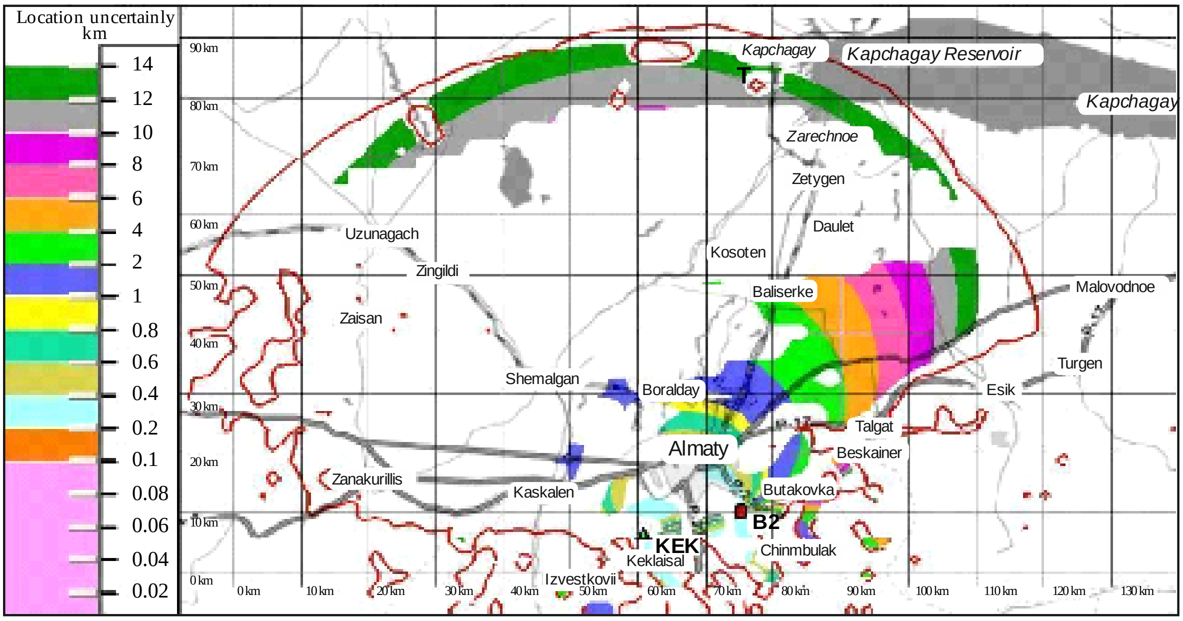

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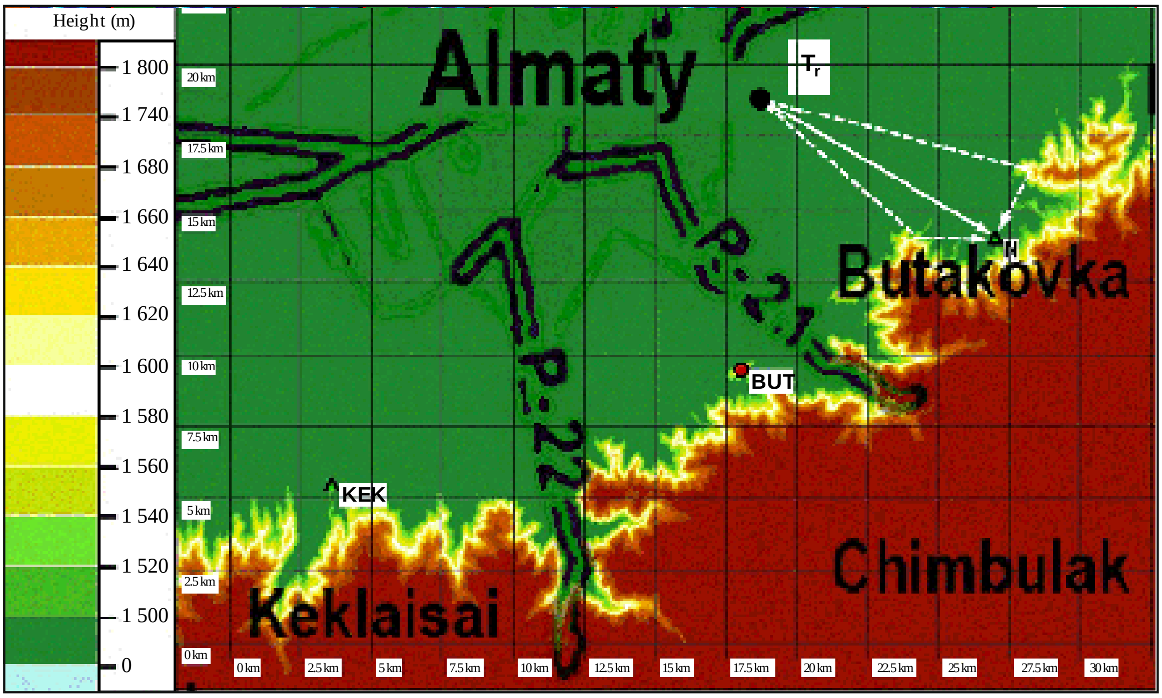
FIGURE A2-4

Siting of stations to reduce the likelihood of reflection effects



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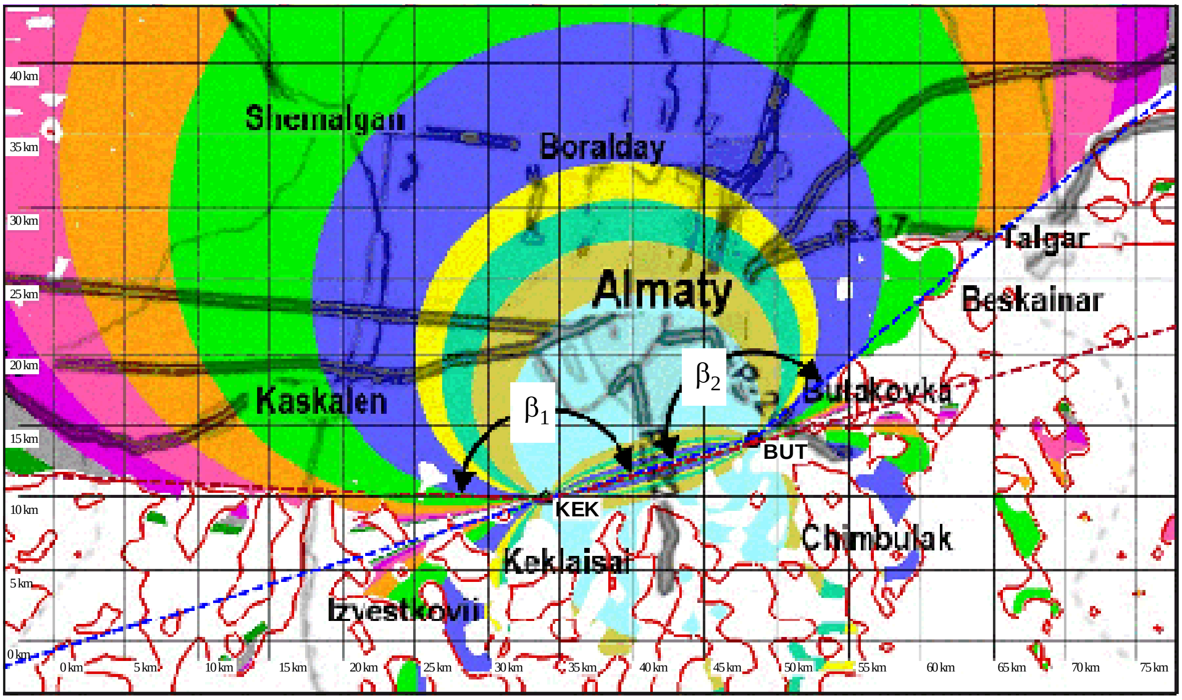
In order to prevent reflection effects from high mountains located further out from the station concerned (in relation to the monitored territory) and from lateral directions, all false bearings resulting from such reflections can be blocked using appropriate software [4]. In the case considered here, as shown in Fig. A2-5, bearings coming to stations KEK and BUT at angles lying outside sectors β_1 and β_2 respectively can be blocked.

In these territories there are a very few towns or villages in the high mountains with radio transmitters of potential interest for monitoring, and in such areas there is virtually no effective monitoring with fixed stations.

FIGURE A2-5

Blocking false bearings generated by reflections from mountains



Report SM.2356-A2-05

At large distances from the group of fixed monitoring stations location uncertainty values may be very high. But this does not prevent effective determination of a place of sought transmitter by a mobile station in such areas as well as in areas outside the LCT, where DF is provided by only one fixed monitoring station, if there is an efficient interaction between these mobile and fixed monitoring stations, as it is described in [5].

A2-4 Final remarks

A mountainous topography can be exploited effectively in order to extend the monitoring coverage zones of a small number of fixed stations throughout the plains adjoining mountain ranges. On the other hand, under such conditions, the selection of suitable antenna sites and careful site surveys are even more critical to ensuring uninterrupted lines of sight in the direction of the monitored area. Measures are also needed to reduce the effect of reflections from nearby mountains situated behind a given station in relation to the monitored territory.

Annex 3

Receiver performance and its impact on network coverage

A3-1 Impact of Receiver performance on geolocation network station separation distances

System sensitivity for a spectrum monitoring station is defined by many different design parameters, including antenna gain, receiver instantaneous bandwidths (IBW), receiver noise figure, receiver instantaneous dynamic range, and receiver phase noise.

The performance specifications of the monitoring receiver will have a direct impact on planned separation distance between nodes on the primary regular network. This, in turn, has an impact on coverage area. Higher performance receivers can allow greater separation and thus a lower number of monitoring stations to cover a particular territory. These principles apply to AOA, TDOA and Hybrid networks. In the following, we use $\boldsymbol{NF_{receiver}}$ as the effective receiver noise figure, that combines the actual receiver noise figure with the effects of instantaneous dynamic range and receiver phase noise. The typical noise figure for a modern receiver is 12 dB.

A3-2 Instantaneous dynamic range

Modern signals operate with steadily increasing bandwidths reaching 20 MHz or wider. In order to effectively analyse these signals, modern SMS systems use wideband receivers. With the increase in receiver bandwidth, an unintended side effect is that it is more likely to have both strong and weak signals present within the receiver bandwidth. The likelihood of the monitoring system installed in the vicinity of strong nearby signals is a real-world problem driven by the fact that the emitter density is constantly increasing.

In order to receive a weak signal in the presence of strong signals the wideband receiver must have high in-band dynamic range or it will not be able to detect weak signals.[4] The effect of the insufficient dynamic range is that weak signals cannot be detected, which is equivalent to increasing the receiver's *effective* noise figure. Note that the effects of strong nearby signals can be further reduced by using receivers that have dual receiver bandwidths, wide and narrow, where the narrow bandwidth (typically 1/10th of wide bandwidth) is used in the presence of extremely strong nearby signals.

A3-3 Phase noise

A receiver's local oscillator is designed to produce as pure a mixing signal as possible, but in practice the achievable purity can vary widely depending on the design. The purity is measured in dB below carrier (dBc) at several offset frequencies. The problem is that local oscillator phase noise, through receiver reciprocal mixing, can mask weak signals in the presence of strong signals. The effect of the reciprocal mixing is again equivalent to increasing the receiver's effective noise figure. In order to minimize the effects of the reciprocal mixing, receiver phase noise must be low. The phase noise specification of a modern receiver should not be less than –100 dBc/Hz in 10 kHz offset.

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[4] Mitigation steps such as notch or bandstop filters to reduce strong signals are not considered in this analysis.

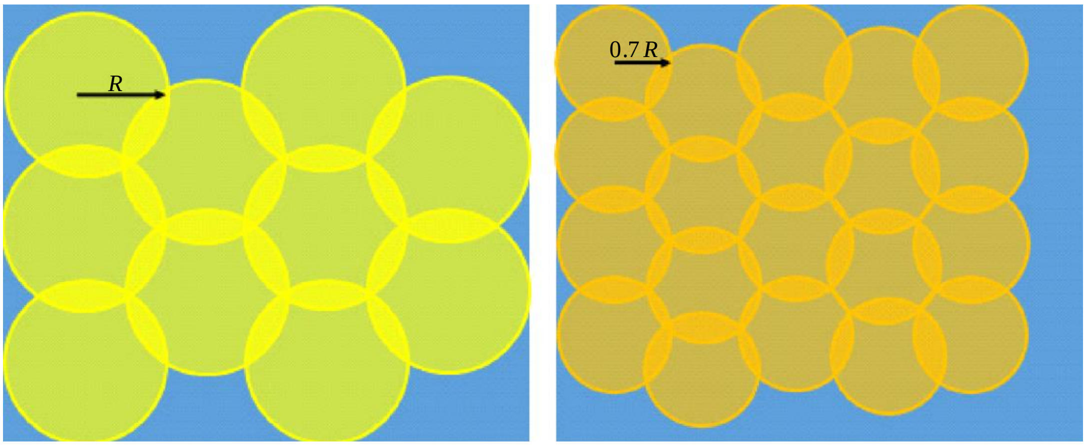
A3-4 Effects on coverage area

Figure A3-1 illustrates the relationship between receiver effective noise figure and the total number of stations required for blanket coverage of a notional area of interest. The Figure on the left shows a network of stations, with $\boldsymbol{NF_{receiver} = X}$**,** resulting in a radius of coverage $\boldsymbol{R}$ and a coverage area $\boldsymbol{CA}$. For these conditions, the area of interest can be covered by approximately nine stations.

The Figure on the right illustrates the situation of a receiver, with a 3 dB higher effective noise figure $\boldsymbol{NF_{receiver} = X + 3}$ **dB**. In this case the coverage radius is reduced to $\boldsymbol{0.7\ R}$ and the coverage area is reduced to ½ $\boldsymbol{CA}$.

FIGURE A3-1

Example of relationship between receiver effective noise figure and the total number of stations required for blanket coverage of a notional area of interest



$NF_{receiver} = X$ $NF_{receiver} = X + 3$ dB

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For every 3 dB increase receiver effective noise figure the number of required monitoring stations approximately doubles for this simple analytical model.

It should be noted that all these arguments are true only for free space. In actual practice, this situation could be worse: in suburban and urban environments in which the ideal 20 log (d) becomes 40 or 50 log (d) – so each 3 dB increase in noise figure results in the need for a greater number of receivers to provide blanket coverage.

More information concerning monitoring receivers is given in section 3.3 of ITU-R Handbook on Spectrum Monitoring (2011 edition).

A3-5 Conclusion

It is important to use receiver equipment that complies with or exceeds current ITU Recommendations. Using the simplest analytical model shows that for every 3 dB increase in receiver effective noise figure, the number of required monitoring stations can at least double.

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