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COGNITIVE RADIO AND TV WHITE SPACES: A NOVEL FRAMEWORK FOR COMBINED LOCALIZATION AND COMMUNICATION ADVANCED SYSTEM DESIGN

MASTER THESIS

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Part I

INTRODUCTION TO TV WHITE SPACES

1 TV WHITE SPACES

At the beginning of this chapter the meaning of the expression "TV White Spaces" will be defined. Then an overview of standards and regulations in U.S and Europe will be provided. The last part of this chapter introduces technical considerations on how white spaces can be exploited.

1.1 THE DIGITAL DIVIDEND

The introduction of digital terrestrial broadcasting, which is underway in many parts of the world, provides many benefits, among which is the professed *digital dividend*. It refers to the spectrum which is released in the process of digital television transition. When television broadcasters switch from analog platforms to digital only platforms, part of the electromagnetic spectrum that has been used for broadcasting will be freed up because digital television needs less spectrum than analog television. The reason is that new digital compression technology can transmit about five digital TV channels by using the same amount of spectrum used to transmit one analogue TV channel. Digital terrestrial television (DTT) delivers an increasing number of quality television programs within the same amount of spectrum that is used by an analogue channel and uses spectrum more efficiently. With the appearance of digital terrestrial broadcasting, namely DVB-T and T-DAB services, it was necessary to reconsider spectrum allocation for broadcast service. Therefore, a new frequency plan was adopted at the Regional Radiocommunications Conference (RCC) in 2006. According to ITU-R Geneva 2006 frequency plan (GE06), three frequency bands are assigned for digital terrestrial broadcasting for the next decade and for 118 countries [1]:

- Band III: 174 - 230 MHz
- Band IV: 470 - 582 MHz
- Band V: 582 - 862 MHz

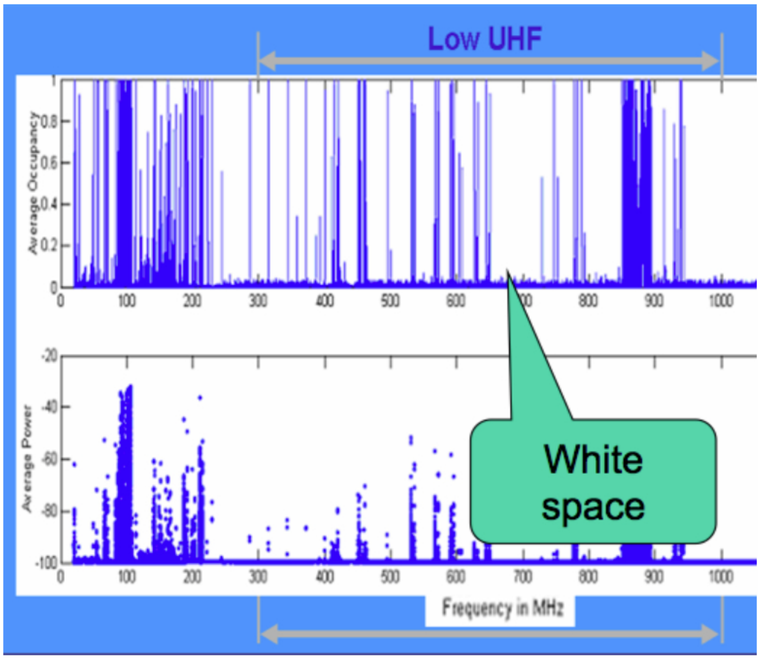


Figure 1: White Spaces scanning example

Definition of TV White Spaces

Another interesting opportunity concerning spectrum exploitation, apart from the UHF band reallocation, is white spaces phenomena. The term *white spaces* is referring to the frequencies licensed for a broadcasting service but not used on designated geographical area. Therefore, many initiatives emerged recently to reallocate those parts of the spectrum as unlicensed and made it accessible to the unlicensed devices under the guaranty that they will not interfere with existing or future broadcasting services. The size of white spaces depends of geographic areas. One example of spectrum scanning in order to visualize white spaces is shown in Figure 1, [2]. As evidenced in [3], TV White Spaces (TVWS) arise for three reasons:

1. The need for guard spaces between analog TV services in the same license area. Because of the superior performance characteristics of digital terrestrial television technologies, the need for guard intervals between DTV services in the same license area can be significantly reduced or eliminated.

2. The need for geographic separation between TV services that are in different license areas but are broadcasting on the same channel

3. The non-allocation of some channels in areas where there is either a limited supply of broadcasting services or limited demand of broadcasting services (typically because of the increasing range of technologies that can be used to deliver broadcasting services).

Still in [3] the authors state that a device, which opportunistically uses these available frequency spaces, is commonly referred to as a *white-space device* (WSD). WSDs can be divided in two types:

1. *symbiotic devices*, which broadcaster have long tolerated
2. *invasive species*, which have acquired secondary (unlicensed or licensed) rigths against the wishes of broadcaster through controversial regulatory decision.

1.1.1 *Symbiotic WSD devices*

They are called *symbiotic* because of their ability to share successfully with broadcasting service, based on compliance with a small set of relatively simple rules that are not controversial and which not require advanced technologies to be implemented. From a regulatory perspective, even though symbiotic WSD are uncontroversial, their use is often based on tolerance rather than legitimacy. An example of this kind of devices is wireless microphones used for Program Making and Special Events (PMSE). They operate in the UHF band but are able to be programmed to operate on a range of channels. The channels chosen depend on the particular area where the microphones are to be used. This approach relies on. Although these microphones are not cognitive in the sense proposed by Joseph Mitola III, they operates in a cognitive fashion as their operators determined the idle channels that they could safely operate in.

1.1.2 *Invasive WSD species*

They are devices interested in the exploitation of TWVS on underlay (UWB) or overlay (Cognitive Radio technologies) basis.

1.2 TVWS STANDARDIZATION AND REGULATION

The TVWS usage by WSDs requires an adequate protection of primary/incumbent users. In this section a summary of the rules in force in the U.S, U.K and Europe will be presented.

1.2.1 *United States*

In November 2008 the United States FCC issued a technical report on the unlicensed use of TV white space spectrum [4]. A number of the requirements to operate in TV white space are based on cognitive radio technology including location awareness and spectrum sensing. There are a number of other requirements also, that are intended to provide protection for the licensed services that operate in the TV bands. These requirements impose technical challenges for the design of devices operating in TV white space spectrum. According to [5] the devices operating according to these rules are referred to as TV band devices (TVBDs) by the FCC. There are two classes of TV band devices: fixed and portable. To simplify the terminology we will use the shorter term portable for the portable devices. Portable devices are further divided into Mode I and Mode II devices.

Fixed Devices

Fixed devices are permitted to transmit up to 30 dBm (1 watt) with up to 6 dBi antenna gain, while portable devices are permitted to transmit up to 20 dBm (100 mw) with no antenna gain. Fixed devices are permitted to use a higher gain antenna as long as the transmit power is decreased dB-for-dB for any antenna gain above 6 dBi. The TV channels include the very high frequency (VHF) channels 2-13 and the ultra high frequency (UHF) channels 14-51. However, there are restrictions on which channels are permissable for use by TVBDs. Fixed devices are permitted in the VHF channels except channels 3-4 and on the UHF channels except channels 36-38. Portable devices are not permitted in the VHF band. Portable devices are permitted on the UHF channels except 14-20 and channel 37. The exclusion for channels 3-4 is to prevent interference with external devices (e.g. DVD players) which are often connected to a TV utilizing either channel 3 or 4. Portable devices are not permitted on channels 14-20 since in 13 metropolitan areas some of those channels are used for public safety applications. Finally, Channel 37 is a protected channel, used for radio

Portable Devices

TV Channel No	Freq. band (MHz)	TV Channel No	Freq. band (MHz)	TV Channel No	Freq. band (MHz)
2	54-60	19	500-506	36	602-608
3	60-66	20	506-512	37	608-614
4	66-72	21	512-518	38	614-620
5	76-82	22	518-524	39	620-626
6	82-88	23	524-530	40	626-632
7	174-180	24	530-536	41	632-638
8	180-186	25	536-542	42	638-644
9	186-192	26	542-548	43	644-650
10	192-198	27	548-554	44	650-656
11	198-204	28	554-560	45	656-662
12	204-210	29	560-566	46	662-668
13	210-216	30	566-572	47	668-674
14	470-476	31	572-578	48	674-680
15	476-482	32	578-584	49	680-686
16	482-488	33	584-590	50	686-692
17	488-494	34	590-596	51	692-698
18	494-500	35	596-602	52	698-704

Red: No unlicensed TVBD operation
Blue: Only fixed devices allowed
Black: All unlicensed TVBD can operate

Figure 2: TV channels in the United States of America open to TVWS

astronomy measurements. Television broadcast signals are protected with a protection contour. The FCC rules provide distances that a TVBD must be outside the protected contour for it to transmit. Within the protected contour there are special rules for operation on a TV channel adjacent to the TV broadcast channel. Fixed TVBDs are not permitted to operate on channels adjacent to the TV broadcast channel. Portable devices are permitted to operate on an adjacent TV channel; however, when operating on an adjacent TV channel, the maximum allowed transmission power is 16 dBm (4 dB lower than on non-adjacent channels). There are also requirements on antenna height for fixed devices. The sensing antenna must be mounted outside and must be at least 10 meters above ground. The transmit antenna must be outdoors and be mounted no more than 30 meters above ground. So if the same antenna is used for both sensing, receiving and transmitting, then that antenna must be between 10 and 30 meters above ground. U.S TV bands are shown in Figure 2.

TV Channel No	Freq. band (MHz)	TV Channel No	Freq. band (MHz)	TV Channel No	Freq. band (MHz)
21	470-478	39	614-622	50	702-710
22	478-486	40	622-630	51	710-718
23	486-494	41	630-638	52	718-726
24	494-502	42	638-646	53	726-734
25	502-510	43	646-654	54	734-742
26	510-518	44	654-662	55	742-750
27	518-526	45	662-670	56	750-758
28	526-534	46	670-678	57	758-766
29	534-542	47	678-686	58	766-774
30	542-550	48	686-694	59	774-782
		49	694-702	60	782-790

Figure 3: TV channels in the U.K open to TVWS

1.2.2 *United Kingdom*

In the United Kingdom, Office of Communications (Ofcom) is the independent telecommunications regulator and competition authority for the communication industries. On the 1st of July 2009, Ofcom published its statement report on TVWS usage [6]. U.K TV bands are shown in Figure 3: OFCOM makes no distinction between devices, they are permitted to transmit from 4 dBm (adjacent channels) up to 17 dBm (in terms of effective isotropic radiated power (EIRP) into an 8 MHz bandwidth).

1.2.3 *Europe*

Following a 2007 European Commission (EC) mandate, in 2008 the Electronic Communications Committee (ECC), under the European Conference of Postal and Telecommunications Administrations (CEPT), issued a report [7] acknowledging the need for further studies on 470-862 MHz band white space use by Cognitive Radio (CR) devices before deciding to proceed to a European recommendation on that matter. According to [7] white spaces devices (WSD) should not be protected form interference among them. However, they must not interfere with licensed primary users, and move to other white spaces channels whenever necessary. Among services to protect in 470-862 MHz band are digi-

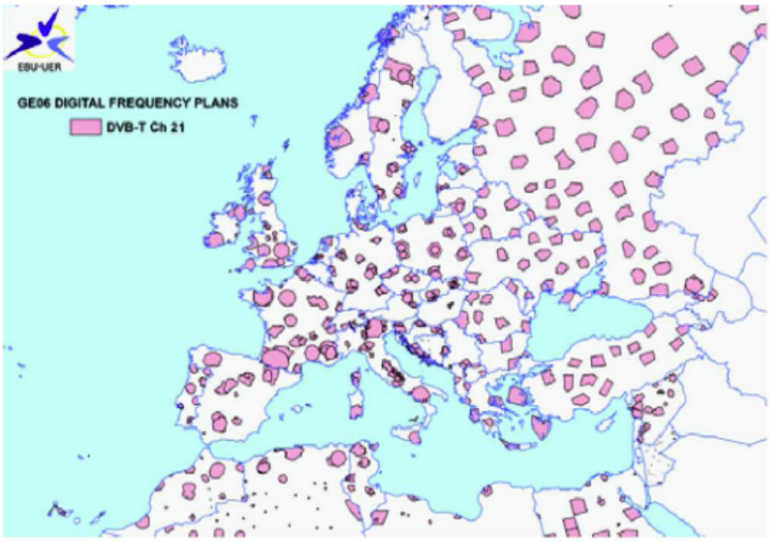


Figure 4: Study results on DVB-T plan entries of Channel 21 in Europe

tal television broadcasting (according to Geneve 2006 Plan, there will be 7 or 8 multiplexes in most European countries), aeronautical radio navigation, military applications (channel 36), radio astronomy (channel 38), program making and special events services (PMSE, channel 69). Meanwhile, sub-band 790-862MHz was reserved for mobile communications and the European white spaces band became 470-790 MHz. At the 22nd ECC Meeting, held on March 2009, it was requested to form working group CEPT SE43 under WG-SE. This group should *"define technical and operational requirements for the operation of cognitive radio systems in the white spaces of the UHF broadcasting band (470-790 MHz) to ensure the protection of incumbent radio services/systems and investigate the consequential amount of spectrum potentially available as white space"*.

The role of CEPT is crucial because Europe is fragmented by many country borders belonging to different regulation agencies, requiring careful harmonization across borders. In particular Figure 4 ([8]) illustrates the DVB-T plan entries of a given channel (channel 21) in Europe and bordering countries over space. As it can be expected, TV broadcasters of a densely populated countries exploit TV channels in particular in the major cities. However, a considerably portion of the countries can be identified as "White Spaces", without any usage of the related frequency band by broadcasters. In those areas in particular, the usage of the related bands by secondary spectrum access approaches can be envisaged. One key concern is to evaluate the expected amount of spectrum available to secondary TVWS devices. Relatively little is known on the availability of white space in European countries. It is generally expected that capacity achieved through the use of white space will be much less in Europe than in the USA, but a solid quantitative foundation of such statements is still missing.

In [9] the authors make a first attempt to quantify, in detail, the availability of TV white spaces in the 470-790 MHz UHF band for a number of European countries. Beyond this, they study also the influence of the propagation model on the estimates of white spaces availability by using two different models. Let us explain this approach.

Let denote by $\mathbf{x}_i$ the ith transmitter's location, its power by P_i, its height by h_i and its operating frequency by f_i. You characterize TV white spaces with a binary label to any space-time-frequency bin. In particular, the target is to evaluate the *indicator function*:

$$I(t, f, \mathbf{x}) := \begin{cases} 0, & \text{when } \mathbf{x} = \bigcup_{i:f_i=f} \mathcal{A}_{nt}^i(t) \\ 1, & \text{otherwise} \end{cases} \tag{1.1}$$

where t,f and $\mathbf{x}$ denote time, frequency and space, and where $\mathcal{A}_{nt}^i(t)$ is the *no-talk region* of the ith transmitter at time t. With respect to the three indicator function's argument, you make the following choices:

- Characteristics of TV networks typically change slowly, in time scales of days, weeks or even months. Moreover, our analysis depends critically on the public availability of the TV network data. Almost all these data appear in the form of current transmitter lists; when changes appear the publishing authority or company typically replaces the old database with a new. The evaluation of the TV white space as a function of time is therefore essentially out of control. In what follows you will drop the time index for reasons of clarity.

- In Europe, TV frequencies have been organized in 8MHz wide channels. You will analyze the white space in the UHF TV channels 21-60. Expressed differently, you will evaluate 1.1 on the frequency grid

$F = \{474, 482, 490, ..., 778, 786\}$ MHz, the center frequencies of these 40 TV channels.

- You evaluate the white space on a grid X having 2 km resolution. In particular we use Lambert's Azimuthal Equal-Area projection [10] with center 10 degrees East and 52 degrees North to obtain this evaluation grid for all our European maps.

With this characteristics of the space-time-frequency bins, you will also calculate the following quantities:

- $S(\mathbf{x}) := \sum_{f \in F} I(f, \mathbf{x})$
- $m_a := \frac{1}{a_0} \sum_{\mathbf{x} \in X} a(\mathbf{x}) S\mathbf{x}$
- $m_p := \frac{1}{p_0} \sum_{\mathbf{x} \in X} p(\mathbf{x}) S\mathbf{x}$

where: $S(\mathbf{x})$ is the total number of channels available at a given location $\mathbf{x}$, m_a is the average number of available TV channels in region *X by area*, m_p is the average number of available TV channels in region *X by population*, $a(\mathbf{x})$ is the area associated with and represented by the spatial bin located at $\mathbf{x}$ and $a_0 = \sum_{\mathbf{x} \in X} a(\mathbf{x})$ is the total area of the considered region; $p(\mathbf{x})$ is the population associated with and represented by the spatial bin located at $\mathbf{x}$ and $p_0 = \sum_{\mathbf{x} \in X} p(\mathbf{x})$ is the total population in the region.

The no-talk region $A^i_{nt}(t)$ of a given transmitter is related to its *service region*, namely the area in which the condition on signal-to-interference-and-noise ratio to make TV reception possible is satisfied. As evidenced by the author, you cannot reasonably declare a protected status for all locations TV reception was possible prior to the appearance of secondary transmitters (characterized by a noise-limited radius) as this would render the whole concept of secondary spectrum usage obsolete. With such a declaration there would be no white space since even the most remote secondary transmitter with the smallest power would cause the interference level at the noise-limited distance from the TV transmitter to increase by an infinitesimal amount. Hence, incorporation of a margin is needed for the white space concept to make sense. As in [11] the authors choose to define the protected locations through a $\gamma = 1\,\text{dB}$ margin of the TV transmitter's link budget. This margin will allow transmission by secondary users with any transmit power and height provided they operate sufficiently far away from

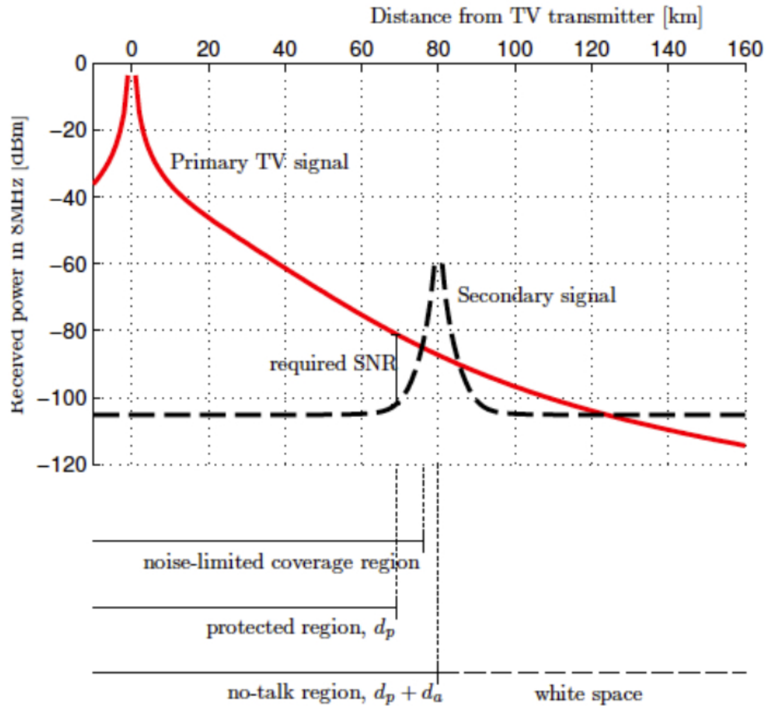


Figure 5: An example of the no-talk distance of a TV transmitter

the protected region. Considering Figure 5, The ith transmitter's no-talk distance $d_p^i + d_a$ is the minimum distance a secondary transmitter must stay away from the ith TV transmitter in order to guarantee a minimum required field strength in all positions inside the protected-circle of radius d_p^i. The transmitter's parameters used in the figure are: 47 dBW transmit power, effective eight 337 m, channel 50 with 64 QAM. These parameters, along the ITU channel model [12], imply a minimum required field strength of 46.6dB(μV/m) and a protection distance d_p of 76 km. The protected region is so defined by the minimum required field strength that ensures proper TV reception. According to the recommendations given in [13] and [14] by the ITU-R, the minimum field strength in dB(μV/m), for analog and digital TV transmitters, is respectively:

$$E_{req}^{analog} = \gamma + 20\log_{10} f - 111.5 \qquad (1.2)$$

$$E_{req}^{digital} = \gamma + 20\log_{10} f - 150.1 + SNR_{req} \qquad (1.3)$$

where f is the center frequency of the TV band in Hz. In Equation 1.3 you consider a noise band of 7.6MHz, a receiver figure noise of 7dB and an half-wave dipole antenna with a 7dB net gain between the transmission-line and the antenna.

The translation of the above link-budget-based definition of a white space depends on the configuration of a TV network and on the characteristics of the propagation environment. Access to the former is provided to the public by a number of European regulators or broadcasters. The two used propagation models are:

1. Statistical model, distance-based
2. Deterministic model, which models the irregularity of terrain taking into account environmental characteristics of the region under test.

The critical parameter of the first model is the distance to a TV transmitter which along to the transmitter power and height determines the no-talk region as:

$$\mathcal{A}^i_{nt}(t) := \{\|\mathbf{x} : \mathbf{x}_i - \mathbf{x}\| < d^i_p(\gamma, P_i, h_i) + d_a(P_2, h_2)\} \quad (1.4)$$

where $d^i_p(\gamma, P_i, h_i)$ is the protection distance of the ith TV transmitter and $d_a(P_2, h_2)$ is the additional provection distance that depends on the transmit power P_2 and height h_2 of the secondary transmitter.

In the second approach you adopt the Longley-Rice irregular terrain model [15]. The Longley-Rice model takes into account a wide variety of factors from terrain shapes to atmospheric diffraction. In this second, irregular terrain propagation model the protected region (the region where the field strength exceeds a critical threshold) has potentially a very complex shape. We use numerical computation to obtain an estimation of the SNR for each transmitter on a dense regular grid, and service areas are formed by thresholding with the required SNR complemented with the additional 1 dB erosion margin. This results in the protection region associated with each TV transmitter. The additional protection distance $d_a(P_2, h_2)$ is then accounted for by extending the no-talk area by including points which are no closer than distance d_a to the protected region.

	population, p_0	area, a_0	nr of transmitters			white space by area		white space by population[7]	
Country	[$\times 10^6$]	[km^2]	analog	digital	modulation	channels, m_a	fraction	channels, m_p	fraction
Czech Republic[1]	10.51	78620	103	318	64 QAM	13.4	34%	14.1	35%
Germany[1]	81.80	357160	75	731	16 QAM	19.2	48%	17.7	44%
Luxemburg[1]	0.50	2608	11	3	64 QAM	21.5	54%	19.8	50%
United Kingdom[5]	62.01	243916	1176	2790	64 QAM	23.1	58%	20.4	51%
Sweden[4]	9.34	442804	0	1194	64 QAM	25.6	64%	21.4	54%
Austria[1]	8.38	83888	134	164	16 QAM	21.1	53%	22.0	55%
The Netherlands[2]	16.58	36996	0	281	64 QAM	23.7	59%	23.7	59%
Denmark[1]	5.53	42564	32	303	64 QAM	24.4	61%	24.1	60%
Switzerland[1]	7.78	41408	6	285	64 QAM	25.3	63%		
Belgium[1]	10.83	30656	20	65	64 QAM	25.6	64%	25.2	63%
Slovakia[3]	5.42	48420	1096	19	64 QAM	26.1	65%	25.8	65%
All 11 European countries	*218.68*	*1409040*	*2653*	*6153*		*22.5*	*56%*	*19.8*	*49%*
US[6]	*306.51*	*7663942*					*79%*		*63%*

[1] http://www.bundesnetzagentur.de/cln_1912/DE/Sachgebiete/Telekommunikation/RegulierungTelekommunikation/Frequenzordnung/Rundfunk/Rundfunk_Basepage.html
[2] http://appl.at-ez.nl/dav/index.html
[3] http://www.teleoff.gov.sk/index.php?ID=377
[4] http://www.pts.se/sv/Dokument/Rapporter/Radio/2008 and http://www.teracom.se/Sandarinformation/Hitta_ratt_tv_mast
[5] http://stakeholders.ofcom.org.uk/broadcasting/guidance/tech-guidance
[6] The white space results are taken from [4, Table II], see the columns labelled low-UHF and H-UHFand appear to relate to the contiguous US.
[7] We use the population density data made available by the European Environment Agency at http://www.eea.europa.eu/data-and-maps/data

Figure 6: TV network characteristics and white space in 11 European countries and the US

1.2.3.1 *Results*

Figure 6 shows the results about how many TV channels are available in the ideal case of zero-power secondary devices. These results reprenset an absolute upper bound on the available TV white space in the sense that any realistic scenario will have to accommodate an additional distance $d_a(P_2, h_2) > 0$. Below the figure the sources used by the authors to obtain data containing the locations and relative heights of the TV transmitters, the frequencies and transmit power they use and their antenna characteristics, of 11 European countries, are listed. For the entire evaluated European region covered by the 11 countries the average availability of the TV channels is 56% of the evaluated band (by area) or 49% (by population). For comparison, we have also added the associated figures for the US taken from [11], that relate to a similar spectrum band 470-806 MHz. Here, white space accumulates to 79% (by area) or 63% (by population). Clearly, affirms that there are less white space opportunities in Europe than in the USA.

In the second case-model, due to the high computational overhead and the high resolution of the obtained data set the authors focus on the situation in Germany. This choice was made also in part due to the highly accurate DTV transmitter data available for this region, including the precise elevation and radiation patterns. They used the terrain data

	Additional protection distance					
	5 km	10 km	15 km	20 km	25 km	30 km
Average number of available channels by area	12.1	9.92	8.51	7.40	6.47	5.68
Average number of available channels by population	11.4	9.17	7.71	6.57	5.69	4.95

Figure 7: Influence of additional protection area on the average number of available channels

set from the Shuttle Radar Topography Mission (SRTM) to carry out the simulations. The results found out by the authors using the second model show that terrain features do play a visible role in the estimated white space availability although the overall number is not drastically changed. Especially the local variability in availability of TV channels caused by terrain that the statistical propagation model does not account for is much higher for the Longley-Rice case. The average number of available channels over the whole area is 19.9 while the population weighted average is 18.7.

Moreover, for realistic system, is interesting to study the influence of increasing the no-talk areas to accommodate for secondary systems of higher transmit power or higher potential total interference. Figure 7 illustrates the obtained results for additional protection margins da ranging from 5 km to 15 km. We see that even relatively conservative addition of 10 km significantly reduces the available white spaces.

Another quantity of interest is the distribution of distances to the no-talk region for different channels. These distances are especially important in scenarios in which the secondary users are allowed to change their transmit powers in order to achieve maximum capacity while still respecting an interference limit at the edge of the primary user service area. Figure 8 shows the box plots for these distance distributions for the different UHF channels. It is interesting to note that the usage of the different channels is clearly highly uneven across the country. These distance distributions can, of course, directly be combined with a suitable propagation model for the secondary-primary interference to yield estimates of the allowed transmit power distributions and, by assuming a specific service model for the secondary, on the corresponding capacities of secondary systems. The key conclusion from these results is that not all

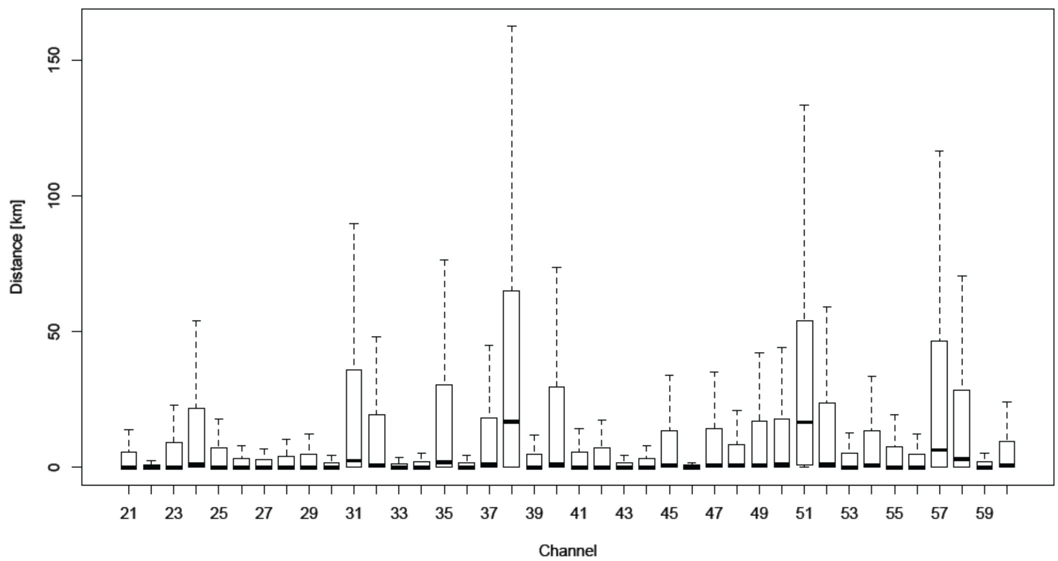


Figure 8: Distribution of distances to the protected area for different channels

white space channels are equal. Under a constant interference constraint, on certain channels much higher transmit powers could be used by secondary users compared to others.

1.3 cognitive radio and access to the tvws

Cognitive radio is being intensively researched as the enabling technology for secondary access to the TV White Spaces. In particular the form of cognitive radio technology known as dynamic spectrum access (DSA). Its aim is to achieve device-centric interference control and dynamic re-use of radio spactrum based on the frequency agility and intelligence offered by cognitive radio technology.

1.3.1 *Cognitive Radio*

Cognitive Radio is a technology that allows the system to obtain knowledge of its operational and geographical environment, established polices and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives and to learn from the results obtained.

1.3.2 *Spectrum Sharing*

In [16] the state-of-the-art in technology, regulation and standardisation of cognitive radio access to TVWS is reviewed: both the FCC and Ofcom have considered three methods for ensuring that cognitive devices do not cause harmful interference to incumbent:

1. *Beacons*. With the beacon method, unlicensed devices only transmit if they receive a control signal (beacon) identifying vacant channels within their service areas. The signal can be received from a TV station, FM broadcast station, or TV band fixed unlicensed transmitter. Without reception of this control signal, no transmissions are permitted. One issue with the control signal method is that it requires a beacon infrastructure to be in place, which needs to be maintained and operated, either by the incumbent or a third party. Furthermore, beacon signals can be lost due to mechanisms similar to the hidden node problem.

2. *Location Awareness*. This location awareness is coupled with Internet access capability for both fixed TVBDs and portable devices, and must be accurate to within 50 meters. This Internet access is utilized to obtain access to a database containing information about licensed transmission in the various TV channels. These licensed transmissions include ATSC (Digital TV) highpower broadcasts, ATSC and NTSC (Analog TV) low-power transmitter, and wireless microphones used by the broadcast industry.

3. *Spectrum Sensing*. The device attempting to access the spectrum must observe the various TV channels and determine if these channels are occupied by any licensed transmission.

In the next subsection the last two points will be deepen, following [5].

1.3.2.1 *Location awareness: geo location*

The FCC rules require both fixed and portable devices be directly connected through the Internet to incumbent databases. The principal purpose of this requirement is to provide a mechanism to inform devices about their neighboring TV/wireless microphone signals and peer devices. Indeed, all TV broadcasting stations (including low-power TV, translators, boosters, etc.) are required to be archived in incumbent databases, and such information essentially overrides the outcomes of spectrum sensing for TV signals. That is, for a device located within the contour of a TV station as indicated in the geo-Iocation database, even if spectrum sensing reports that the TV channel is unoccupied (say, due to shadowing), the device still needs to view this channel as occupied by TV. The FCC rules specify a precision of ± 50 meters for TVBDs' locations. For fixed TVBDs, their locations are manually set when they are installed. Since their installation is thoroughly planned and performed by professionals, obtaining their locations is by no means a technical challenge. For portable TVBDs, if global positioning service (GPS) is equipped and TVBDs are outdoor, obtaining their geo-Iocations may still be less a technical challenge.If no GPS is available or if TVBDs are indoor, then obtaining geo-locations becomes a challenging task.

1.3.2.2 *Spectrum sensing*

In the FCC rules, the main requirement on spectrum sensing is that a TVBD should be able to detect the presence of (digital and analog) TV signals and wireless microphone signals at a received power level -114 dBm. To understand this sensitivity requirement, we note that the noise power level of a 6 MHz TV channel is typically around -100 dBm (including a 6 dB noise figure), and therefore the -114 dBm received power level translates into a SNR of around -15 dB. Furthermore, since for lower UHF TV band the effective antenna size is reduced compared with higher RF frequencies, a phone-form factor receive antenna will have a low antenna gain, say, $-5 \div -3$ dB. Consequently, the spectrum sensing problem for each single TVBD becomes detecting the presence or absence of certain target signals (digita-analog TV, wireless microphone) across a bandwidth of 6 MHz, and at a SNR of $-20 \div -18$ dB. As previously said, there are three types of signals to be sensed: analog TV, digital TV and wireless microphone. The digital TV in the United States follows the ATSC standard. TV programs are modulated using 8-level vestigial sideband modulation (8VSB) and the modulated signal occupies almost the entire 6 MHz TV channel uniformly, with a pilot carrier which contains approximately 7% of the total signal power and is located at approximately 310 kHz above the lower edge of the channel. Figure 9 displays the received powerspectral density (PSD) of a typical ATSC signal. The analog TV in the United States follows the NTSC standard, and may still be used for low-power local broadcasting after the DTV transition. The luminance part of signal is amplitude-modulated, and its (video) carrier, containing more than half of the total signal power, is located at 1.25 MHz above the lower edge of the channel. The color part of signal is quadrature-amplitude-modulated with suppressed carrier, and its subcarrier is approximately 3.58 MHz above the video carrier. The audio part of signal is frequency-modulated, and its subcarrier is 4.5 MHz above the video carrier. Figure 10 displays the received PSD of a typical NTSC signal. Wireless microphones, as the most common Part 74 devices, are allowed by the FCC to transmit in TV channels which are not occupied by ATSC/NTSC signals, provided that their transmit power and bandwidth meet certain requirements. The maximum bandwidth of a wireless microphone is 200 kHz. Therefore, multiple such devices may operate within a single TV channel, and their carrier frequency locations are not a priori fixed, unlike carriers of ATSC/NTSC signals as described in the previous paragraph. There is no specific requirement on the modulation scheme for wireless microphones, whereas in the TV band, analog frequency modulation (FM) is the most common practice. Figure 11 displays the received PSD of a typical wireless microphone signal within a TV channel.

For ATSC/NTSC signals, spectrum sensing is a simpler task compared with wireless microphone signals, which will be elaborated shortly. The key observation is that, such signals statistically do not resemble white Gaussian noise, rather they exhibit narrowband features through the ATSC pilot, the NTSC video carrier, etc. Furthermore, the frequency locations of those narrowband features are fixed, and the "local" SNR in their vicinity can be boosted through appropriate filtering. The spectrum sensing problem hence can be posed as a binary hypothesis test between pure noise and a carrier with unknown phase in noise; or, specifically for NTSC, as a binary hypothesis test between pure noise and a stochastic signal in noise. Both of the two hypothesis test problems have been well understood ([17]), and have

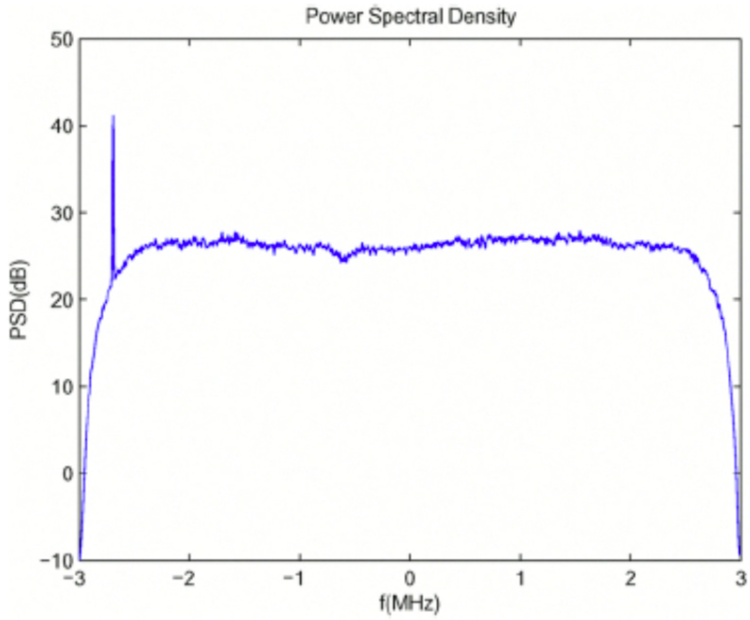


Figure 9: Received PSD of a typical ATSC signal

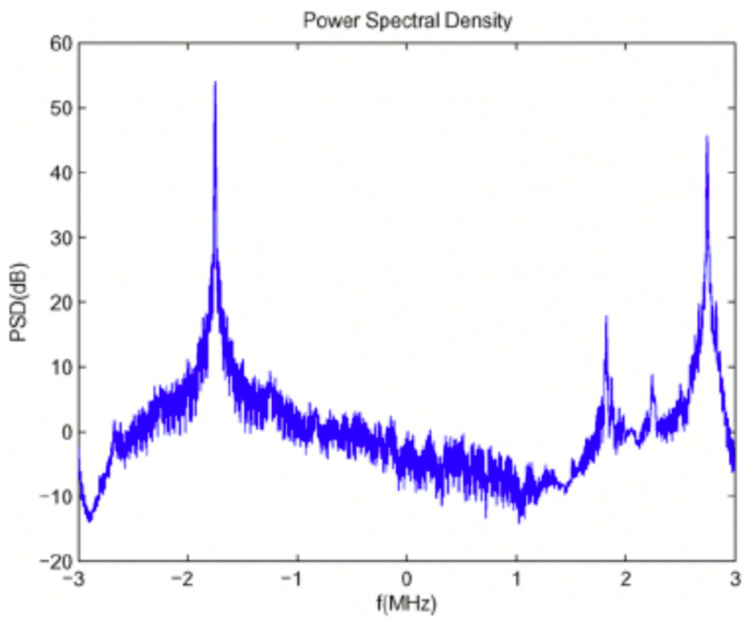


Figure 10: Received PSD of a typical NTSC signal

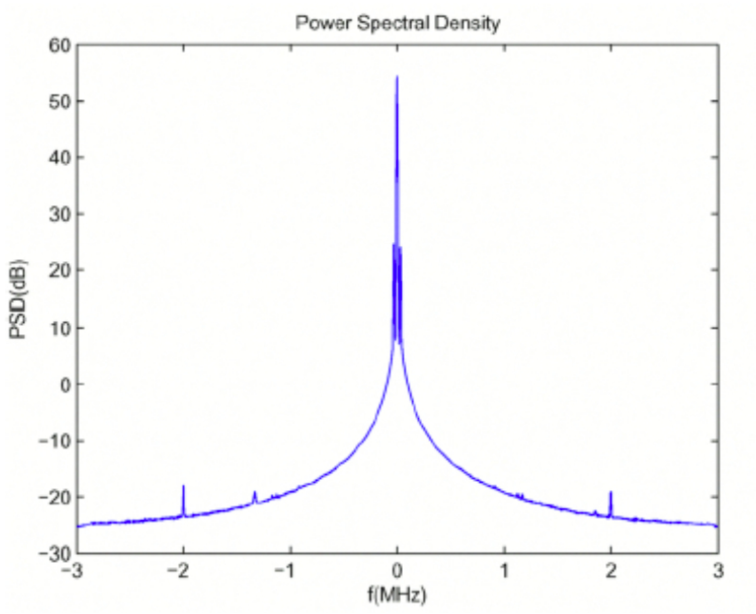


Figure 11: Received PSD of a typical wireless microphone signal

been demonstrated as effective using real signals collected in laboratory. The main challenge in spectrum sensing is for wireless microphone signals. Theoretically speaking, even though the carrier frequency location of a wireless microphone signal is unknown in advance, it is still possible to distinguish between such a signal and pure noise, because as illustrated in Figure 11 the PSD of wireless microphone signals exhibits a narrow spike which, with high probability, would not be produced by white Gaussian noise. Indeed, laboratory tests have shown that sensing techniques based on this idea can reliably detect the presence of wireless microphone signals even as low as - 20 dB SNR. This fact is not entirely surprising, because a wireless microphone signal can at most occupy 200 kHz within a 6 MHz TV channel, and therefore within the 200 kHz bandwidth the SNR can at least be boosted by $\frac{6 \cdot 10^6}{200 \cdot 10^3} \approx 15\text{dB}$. The challenge, however, is that such narrowband spikes are also observed in received signals without the presence of wireless microphones. In other words, the spectrum sensing problem is not the binary hypothesis between pure noise and wireless microphone signal in noise, because the "pure noise" hypothesis indeed contains narrowband interference. To illustrate this, Figure 12 displays the received PSD of a TV channel, which contains one wireless microphone signal (located at 1 MHz above the lower edge, and with power level approximately

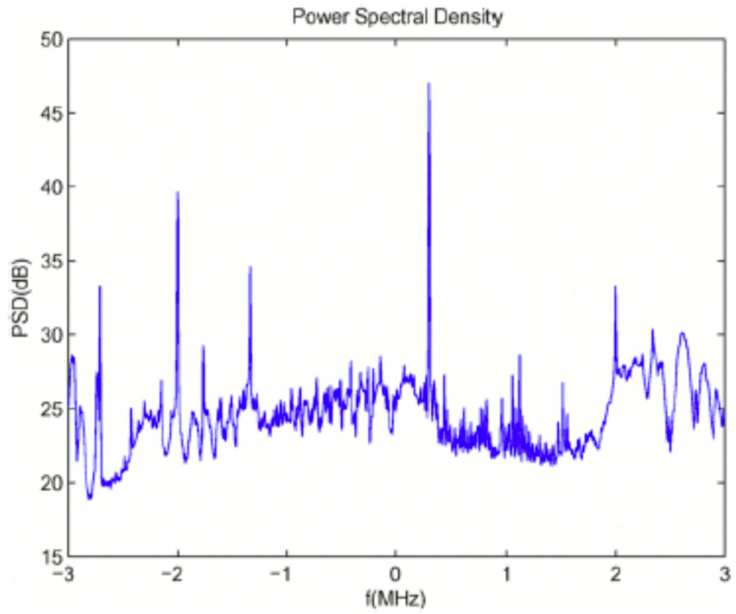


Figure 12: Received PSD of a typical channel with wireless microphone signal and narrowband interference signals

-105 dBm) and a number of narrowband interference signals from unknown sources. There are different possible sources of narrowband interference. Spurious emissions and unintentional transmissions are universal from all types of electronic devices, and some reside within the TV band. For spectrum sensing these interference signals turn out to have strengths similar to the signals to be sensed, say, wireless microphone signals below the noise floor. In addition, other sources of narrowband interference include leakages from adjacent TV channels, quantization noise from analog-to-digital conversion (ADC), and RF impairments like nonlinear inter-modulation. From the preceding discussion, it is evident that spectrum sensing of wireless microphone signals mandates a classification procedure, in order to expurgate narrowband interference. Without doing so, it is likely that most of TV channels would be decided to be occupied and consequently no TVBD would be allowed to operate. There are two main technical hurdles in the classification problem. First, there lacks a technical standard among different wireless microphone manufacturers. All design parameters (e.g, operational frequencies, PM frequency deviation, side-tone placement, etc.) can drastically vary among manufacturers and device models. Therefore, it is difficult to abstract features that are stable and common for all wireless microphones. Second, analog PM signals, in their general form, is nothing but a carrier wave (CW) with a gradually changing phase. If the phase changes too slowly with time, say, when the input to a wireless microphone is silent, then the resulting wireless microphone signal would not be much different than CW-like spurious emissions. The spectrum sensing problem may be most effectively solved from a pattern recognition perspective; alternatively, the theory of robust detection may prove to be another useful tool. It is still unclear how the challenge will be settled eventually, or if there exist any fundamental performance limits. Nevertheless, the bottom line is that, for spectrum sensing at low SNR, the problem need be posed carefully in a way that does not oversimplify the reality.

1.3.3 *Operational and technical requirements for WSDs in the UHF band: an "European" point of view*

In the previous sections we have seen some techniques and rules stated by the FCC about TVWS access and power emissions for devices. In Europe, all that is considered in the technical report of the ECC [18] published in 2011. In this report the emission limits, the protection criteria for the incumbents and the cognitive technique for TVWS are studied.

The different protection requirements for services/systems within the band 470-790 MHz as well as protection of services and system adjacent to the band have lead to different emission limits. The two main approaches with WSD emission limits are:

- Location specific output power: the allowed output power can be determined for each location, frequency and device type/class within the database. Such an approach requires the use of geolocation. An upper limit of the output power for each device type/class could be defined, with the understanding that devices could operate at any power between zero and their associated upper limits
- Fixed output power: there may be a few device types (such as portable and fixed) for which the key main characteristics are predefined, and certain fixed output power limits are allowed for them to be used outside the protected areas. The limits may be different for

use of adjacent channels and for other channels. This approach has currently been chosen by the FCC (for example, 20 dBm for portable devices as seen in the previous section). In this case the specific device types and associated e.i.r.p. should be defined.

The location specific output power approach may increase the complexity of a WSD and the system due to the considerable amount of calculations to be performed by the database and somewhat increased amount of information to be passed between the WSD and a geo-location database. Furthermore, some of the data, such as a precise terrain model needed in the calculation may not be easily available. This type of calculations is however already performed today by administration to assign licenses for specific devices and to coordinate transmitters with neighboring countries so it is the amount of calculation that may increase, not the complexity. On the other hand the location specific output power approach may allow higher WSD output power than in the fixed output power approach in places where it is possible from the protection point of view. This may be useful for some use cases and deployments, e.g. in the rural areas. Additionally, WSDs may be allowed to operate with lower output power in some locations where it would not be allowed with the fixed output power approach. This would lead to more efficient use of the spectrum. The fixed output power approach would be simpler from the device and database point of view but could in some locations be more restrictive for the devices due to rigid power limits. Having predefined device types with fixed power limits and technical characteristics may also restrict the emergence of new innovative devices. In conclusion, location specific output power seems to be better from spectrum usage view. The allowed emission parameters to be defined are directly linked to the technologies used by the services to be protected from WSDs, and especially to the performance of potential victim receivers. They should be chosen in such a way that transmissions from WSDs will not cause harmful interference to protected services, neither in co-channel nor in any adjacent channel.

Also for European countries *spectrum sensing* and *geo-location* have been proposed as the main techniques to assist the white space devices in finding unoccupied channels. With spectrum sensing, WSDs try to detect the presence of the protected incumbent services in each of the potentially available channels. Spectrum sensing essentially involves conducting a measurement within a candidate channel, to determine whether any protected service is present. When a channel is determined to be vacant, sensing might also be applied to adjacent channels to determine what constraints there might be on transmission power, if any. So for sensing only WSD some channels may have to be permanently excluded, because the occupying service is not amenable to detection by sensing, such as passive service. For example, in the band 608-614 MHz some countries have stations for radio astronomy services which cannot be protected by sensing. A significant advantage of spectrum sensing (stand alone) would be that it does not rely on any existing local infrastructure, such as connection to a database. This could be important where access to the internet is more limited, or when WSDs are used to provide only local connectivity between multiple devices, without requiring access to e.g. the Internet. However, if sensing thresholds are to be set very low in order to protect existing services, this will result in increasing complexity as well as a reduced number of available channels. This would reduce the potential value to end users, particularly in areas of higher population density, and would hinder commercially viable deployment numbers of the WSD technology. Key parameters for spectrum sensing include:

- Evaluation of sensing threshold
- Periodicity of re-sensing on channels that have been detected as vacant, because sensing decives should also periodically re-sense the channel. This will allow them to detect changes in the presence of incumbent services, in a channel previously considered vacant or in one or more of the adjacent channels.

Sensing methods can be in general divided to two categories: energy detection and feature detection. The energy detection method is used to detect the signal power in the channel under study. The detector can be either wide band matching the channel bandwidth or narrow band with a possibility to slide it across the channel. The advantage of an energy detector is that it is independent of the radio system to be detected and as such future proof and capable of adapting to any new system introduced into the band. A disadvantage is the required low sensitivity due to the noise floor and the possibility of false detections. In case of a very low required detection thresholds an energy detector alone might not be a feasible solution, but can perhaps be used as one element in the detection process. A feature detector would use certain known characteristics of the signal that is to be detected. This may be a specific pilot carrier signal, preamble, continual or scattered pilots in an OFDM signal, certain periodicity (GI) or sequence in the signal in the time or frequency domain. Using these features will result in a processing gain, which will enable detection below the noise floor in the usual sense. It should be noted that the feature detectors are not in general trying to demodulate the signal and thus are not able to access most of the information carried by the signal. A drawback in the feature detector is its dependence on the specific features and that it may have difficulties to adapt to any new radio system introduced by the incumbent in the band later.

In [18] are also defined the criteria to determinate the sensing threshold for all the incumbents that have to been protected: broadcasting service, program making and special event, radio astronomy service and aeronautical radionavigation. It is not a simple task, moreover designing sensing detectors into WSD has some practical challenges. For example one is that the required tuning range would have to be very wide if the WSD is designed to operate over the full UHF-band. The personal/portable WSD will probably include several radio Rx/Tx systems as well as high processing power, memories and displays etc. components. The high speed clocks and busses in the device electronics are generating noise like wide band interference typically at the frequencies of interest for WSD. As the sensing receiver antenna is built in to the device, the sensing receiver will pick up this noise. State-of-the-art implementation of devices can decrease the noise level, but it is obvious that building an effective shielding for the whole TV WS frequency band will be very challenging and it is very probable that self generated noise is another factor in decreasing the sensing sensitivity in such device. Moreover sensing a PMSE signal is very different from sensing DTT signals and, hence, different algorithms are needed for sensing. In that report is shown that sensing only will not provide adequate protection to the broadcasting service, taking into account current technologies. This means that there is a need to employ geo-location with access to database. In cases where other approaches such as geo-location in connection with access to database can provide sufficient protection to the broadcast service, sensing should not be a requirement. The potential benefit of using sensing in addition to the geo-location database needs to be further considered. In the geo-location approach WSDs would measure their location and consult a "geo-location" database to determine which frequencies they can use at their location (i.e. the location which they have indicated to the database). WSDs are not allowed to transmit until they have successfully determined from the database which channels, if any, are available in their location. This requires that the initial access to the database is done by some other means than using white space frequencies. In some cases, for example if a WSD is connected to an access point, one WSD may act as a proxy for the database queries for another WSD or a set of other WSDs. The querying WSD would be called the master WSD and the WSDs it does the query for would be called slave WSD(s). In this case the master WSD would have to ensure in an appropriate way that the slave WSDs operate according to the constraints returned by the database. Depending on the particular implementation this may require that the master WSD has some form of control over the operation of the slave WSDs. Again in [18] there is a interesting description on how this approach works. Let's look at key issues. All the geographical area covered by a geo-location database is represented as pixels which are areas of predetermined dimensions (see for example Figure 13). Each pixel is associated with a list of available frequencies and other relevant data that are provided to cognitive devices querying the database. The exact dimensions of a pixel may depend on the planning decisions made in populating the database. The size of the pixel is a trade-off. Too large a pixel would result in a larger sterilisation than necessary, too small a pixel would result in large number of calculations for the database and a larger data transfer to the device than needed. The size can be selected by each national administration. It should be noted that the area associated with the location as determined by a WSD may cover one or more pixels, depending on the location accuracy of the device. This is in order to take into account the fact that there is an uncertainty about the actual device location, which is at a very high probability somewhere within the uncertainty area associated with the

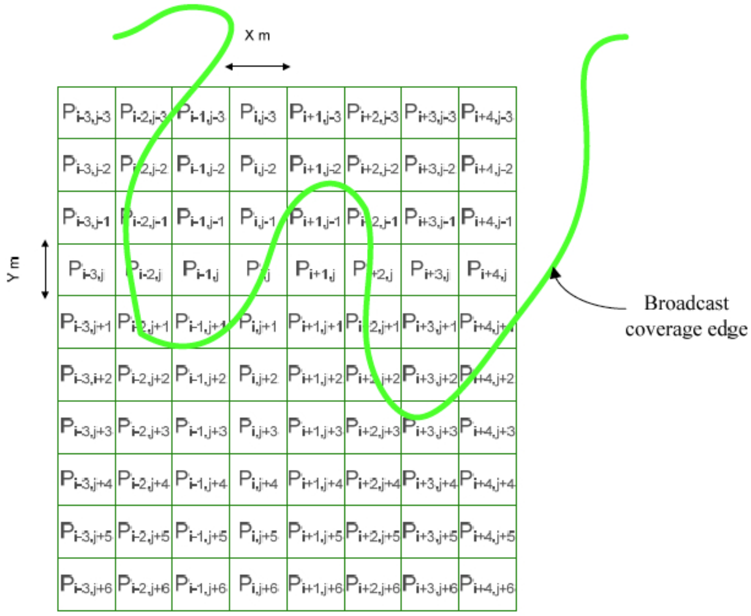


Figure 13: Illustrative example of geo-location database pixel granularity

reported device location. When a WSD, which satisfy all the necessary requirements and so which is able to communicate with the geo-location database and/or with the other WSDs if it acts as the master of a master-slave deployment, wants to discover if there are available channels, it needs to communicate the following informations to the database:

- Location: The location is the current position of the WSD expressed in terms of geographical coordinates as determined by means of a geo-location method.
- Location accuracy: The location accuracy is the absolute accuracy, with which the geographical position of the WSD is determined. It is expressed in terms of an uncertainty radius around the location.
- Device type: Providing information about the type of device, such as the device class will allow information to be returned according to device capabilities and interference characteristics.
- Device ID/model
- Expected area of operation (optional): The device could opt for downloading the information for an area. For example, if the device was aware of its speed

of movement it might opt for a small radius in the case it was moving slowly or a larger radius when moving quickly.

Regarding the database, it has to transmit the following informations to the WSD:

- Available frequencies: that is the frequencies that could be used within the deviceÕs location. Frequency information might be based on a particular bandwidth or alternatively might be provided as a start and end frequency.
- Maximum transmit power: it should be provided for each location, device class and channel assignment.
- Time of validity of the information provided: this parameter defines the time how long the available frequencies and the associated emission limits can be used without re-consultation by the WSD in its location or in the area the WSD addressed in its query.
- If sensing is required (optional requirement): This information flags the need of sensing in conjunction with the geo-location at a given frequency. This would allow flexibility in working with, for example, license exempt wireless microphones that operate in some countries without being registered in the database. If sensing is needed then the database could also return details of what type of device it is necessary to sense and the sensitivity level required in that country.

In this section we have seen that the management of all the aspects concerning the discovering of available channels and the transmission of informations in these frequencies are not very simple tasks. In the further sections and chapters we investigate the possible benefits which TVWS can bring in order to justify these efforts.

1.4 WHITE SPACES: THE NEW WIFI?

1.4.1 *IEEE 802.11af*

Applications that could benefit from white spaces operation is certainly Wi-Fi at TV frequencies. It could be useful for:

1. Rural broadband access for subscribers in densely forested areas. If there is a line of sight, Wi-Fi at 5 GHz is more useful (and has more capacity and low cost) but when subscribers are hidden by trees, TV frequencies are scattered less.

2. Wireless LANs inside heavy masonry buildings or those with plaster on metal wire lath.

In 2008 Google and Microsoft announced their interest in using TVWS for an enhanced type of Wi-Fi like Internet access, called Wi-Fi 2.0, Wi-Fi on steroids, or White-Fi. As a matter of fact, in September 2009, a TVWS Study Group (SG) was formed by the IEEE 802.11 WG to investigate the possibility of a WLAN TVWS standard. The TVWS SG held two meetings in September and November 2009, and produced a document known as the Project Authorization Request (PAR). This was then reviewed and approved by the IEEE Executive Committee (EC) in November 2009. As a result of the approval, the TGaf was officially formed in January 2010. IEEE 802.11af (as mentioned above, also known as Wi-Fi 2.0 or White-Fi) is a technical group which aims at defining an "An amendment that defines modifications to both the 802.11 physical layers (PHY) and the 802.11 Medium Access Control Layer (MAC), to meet the legal requirements for channel access and coexistence in the TV White Space" [19]; in fact the purpose is to adapt 802.11 to TV white spaces operations, that is in another frequency band than the original ISM (or UNII at 5 GHz) frequency band. Due to this lower frequency one can expect a better indoor coverage (lower path loss at lower frequency, especially when compared with UNII band at 5 GHz). Other expected advantage is to find a substitute to crowded ISM bands suffering from interferences. Among the topics to be addressed in this technical group there is the proposal of an OFDM PHY layer having the capability to use up to 4 contiguous TV channels and non-contiguous ones. The aim is to have as few modifications of existing 802.11 PHY as possible. Sensing is also a study item, although the use of TVWS database seems mandatory and is expected to provide much better performance, but it may be of interest to ensure coexistence of either 802.11af or non 802.11af devices in the same TV channels. If we consider that 802.11af access points are connected to internet (via a copper line or a fiber) the use of TVWS database seems natural. According to [20]

IEEE 802.11af can be modeled as a wireless network with a Cognitive Radio enabled access point and associated Cognitive Radio devices as end terminals. The CR-APs operate on spectrum WS via spectrum trading schemes, and the thus incurred time-varying spectrum availability introduces new challenges. For example, upon appearance of Primay Users in a leased channel, the AP should relocate its clients in the channel, which requires eviction control of in-service customers in case the remaining idle channels cannot accommodate all the spectrum demands. Although Wi-Fi over WS is still in its infancy, its resemblance to today's Wi-Fi hotspots suggests that it may become a "killer application" in CR-based wireless networks. By utilizing more favorable spectrum bands than the ISM, the new Wi-Fi must be able to support QoS guarantees and resource-intensive multimedia services more easily than the current Wi-Fi.

1.4.1.1 *A practical example of WhiteFi*

In [21] is presented a prototype system which represent a very important example of WiFi-over-TVWS: the WhiteFi. Indeed, according to the authors, WhiteFi is the first network prototype that demonstrates the feasibility of Wi-Fi like networking over UHF white spaces. To support this statement they provide detailed experimental and simulation results. First it is important to understand the differences between white spaces and the popular ISM bands where Wi-Fi devices operate. First, in both bands there is spatial variation in spectrum availability, but the impact of this variation is higher in white spaces than in ISM bands. This is because the FCC ruling requires non-interference with wireless transmissions of primary users (incumbents). Second, since the incumbents can operate in any portion of the white spaces, the network must be designed to handle spectrum fragmentation, with the possibility of each fragment being of different width. A UHF channel is narrow, and prior research has shown that aggregating contiguous channels improves throughput. Consequently, the network must support variable width channels. Third, RF transmissions in white spaces are subject to temporal variations because wireless microphones can become active at any time without warning. Some experiments show that even a single packet transmission causes audible interference during wireless microphone transmissions. Consequently, both the AP and its clients must disconnect and then rapidly reconnect using a different available channel. The implication of the spatial variation for a white space wireless network is that an Access Point must not naively select channel(s) to operate on based solely on its own local observation of spectrum availability. The AP must take into account the availability of spectrum at its client as well. As regarding the spectrum fragmentation: the radios need to use variable channel width (different fragments width). Compared to Wi-Fi, the use of variable channel widths introduces two new challenges. First, it makes channel assignment more challenging, since APs now occupy a range of channels, rather than just one. Second, it increases the the time taken for nodes to discover APs. This is due to a limitation of techniques that can achieve variable channel widths on Wi-Fi cards. The temporal variation, due in particular to the widespread use of the wireless microphone, is a very hard problem since wireless miss can be turned on at any time and both clients and APs should detect their presence on a channel and move away from that channel. Furthermore, if only a client or an AP detects a mic, each must have a means of informing the other of the channel switch without inducing interference. The proposed network architecture of WhiteFi is based on three key components which try to solve the problems mentioned above:

- A novel spectrum assignment algorithm that is able to handle spatial variation of the spectrum as well as spectrum fragmentation
- An efficient. time-domain signal analysis technique, called **SIFT** (Signal Interpretation before Fourier Transform), that allows clients to rapidly discover APs transmitting on a range of channel widths
- a *chirping* protocol that permits a client to indicate a sudden disconnection from the AP due to a channel conflict with an incumbent, without interfering with the primary user.

1.4.2 *IEEE P1900.7*

In February 2011the Dynamic Spectrum Access Networks (DySPAN) standards committee proposed in a PAR a new

P1900-series standard: the IEEE P1900.7 standard. This standard specifies a radio interface including medium access control (MAC) sublayer and physical (PHY) layer of white space dynamic spectrum access radio systems supporting fixed and mobile operation in white space frequency bands. The proposed standard will support the other IEEE 1900 standards, such as P1900.4a for white space management, P1900.5 for policy languages, and P1900.6 to obtain and exchange sensing related information (spectrum sensing and geolocation information). Also, the proposed standard may support other standards, for example, P802.19.1 for white space coexistence. It is beneficial to develop a new white space radio system standard because, compared to the other standards with the same scope, (like ECMA-392 standard, IEEE P802.22 draft standard, and IEEE P802.11af draft standard) it will have the following new features:

- Full mobility support including handover
- Support of cellular and mesh topologies
- Power efficiency for mobile and low power users
- Multichannel support
- Support of inter-system coexistence

Part II

A NOVEL FRAMEWORK...

2

TVWS: A NEW RESOURCE FOR LOCALIZATION AND COMMUNICATION SYSTEMS

2.1 INTRODUCTION

In the previous chapter we introduced the (work in progress) standards which should allow to use Wi-Fi in 470-790 MHz frequency band. The use of such band of frequencies instead of the ISM one could be more advantageous not only in terms of interference with the overcrowded-ISM devices but also for localization applications and communication resources saving thanks to its better characteristics of propagation. In this chapter we try to evaluate this latter type of advantage: we first describe the localization technique considered and give two theoretical models for the localization estimation error in order to comprehend how effectively the use of TV bands can improve localization performance. Then we use Matlab simulations to make a comparison between the use of 802.11/x (the traditional WiFi) and the WiFi in TVWS in both localization system and communication system (for example: home networks).

2.2 A SURVEY ON LOCALIZATION ERROR

Using wireless devices to provide location is an emerging area that will impact a diverse set of applications including those in asset tracking, workflow management, geographic routing, and physical security. In this thesis we use a localization algorithm based on the *lateration* approach because it is one of the most popular method. This approach involves two phases:

Choice of localization algorithm: RSS and LLS Lateration

1. **Ranging**. The purpose of this phase is to estimate the position of the targeting device to each reference node. A variety of modalities can be used to perform ranging such as Received Signal Strength (RSS), Time Of Arrival (TOA), Angle Of Arrival (AOA), Time Difference Of Arrival (TDOA) and so on. We decide to employ RSS to perform ranging because given that wireless

devices are carried by many people and objects, and all modern radio chipsets include the hardware necessary to measure the received signal strength (RSS) of transmitted packets (WiFi devices provide a received signal strength indicator (RSSI) as a built-in function), there is a tremendous cost and deployment advantage to re-using the existing RSS infrastructure of the communication network for localization.

2. **Lateration**. Its aim is to estimate position of the target through two methods: *Nonlinear Least Squares (NLS)* and *Linear Least Squares (LLS)*. In this thesis we consider 2D relative lateration, that is the action of computing the position of a device with a set of reference nodes which share a common system of coordinates.

We use the following notation:

- $\mathbf{p} = (x, y), \hat{\mathbf{p}} = (\hat{x}, \hat{y}) \in \mathbb{R}^2$ are the position and the estimated position of the targeting device respectively.
- $\mathcal{R}$ is the set of reference nodes, $\mathcal{R}_i = (x_i, y_i)$ is the position of the ith reference node (known).
- $d_i, \hat{d}_i$ are the distance and the estimated (by the RSS ranging) distance of the target position to the ith reference node $\mathcal{R}_i$.
- n is the number of reference nodes.

In NLS, from the estimated distance $\hat{d}_i$ and known position $\mathcal{R}_i$, the position (x, y) can be estimated by finding $(\hat{x}, \hat{y})$ satisfying:

$$(\hat{x}, \hat{y}) = \arg\min_{x,y} \sum_{i=1}^{n} \left[\sqrt{(x_i - x)^2 + (y_i - y)^2} - \hat{d}_i \right]^2 \tag{2.1}$$

However NLS usually requires high computational complexity and is difficult to analyze. To obtain a linearized problem we follow the approach of [22] where the position is estimated as the interception of n circumferences:

$$\begin{cases} \sqrt{(x_1 - x)^2 + (y_1 - y)^2} = d_1 \\ \sqrt{(x_2 - x)^2 + (y_2 - y)^2} = d_2 \\ \cdots \\ \sqrt{(x_n - x)^2 + (y_n - y)^2} = d_n \end{cases}$$

This system can be rewrite in a set of linear equation in (x, y), obtaining:

$$\mathbf{Ap} = \mathbf{b} \tag{2.2}$$

where:

$$\mathbf{A} = -2 \begin{pmatrix} (x_1 - x_n) & (y_1 - y_n) \\ (x_2 - x_n) & (y_2 - y_n) \\ \vdots & \vdots \\ (x_{n-1} - x_n) & (y_{n-1} - y_n) \end{pmatrix} \tag{2.3}$$

and

$$\mathbf{b} = \begin{pmatrix} \hat{d}_1^2 - \hat{d}_n^2 - x_1^2 + x_n^2 - y_1^2 + y_n^2 \\ \hat{d}_2^2 - \hat{d}_n^2 - x_2^2 + x_n^2 - y_2^2 + y_n^2 \\ \vdots \\ \hat{d}_{n-1}^2 - \hat{d}_n^2 - x_{n-1}^2 + x_n^2 - y_{n-1}^2 + y_n^2 \end{pmatrix} \tag{2.4}$$

In the newt subsections we give theoretical models to understand what determines the estimation error level.

2.2.1 *Model I: an algebraic upper bound for the localization error*

Under the assumption that $n \geqslant 3$ (we need at least of three circumferences to determine a unique position) $\mathbf{Ap} = \mathbf{b}$ is an overdetermined system, so we have to find the solution as a solution of a least squares minimization problem. Defining $\xi = \mathbf{b} - \mathbf{Ap}$ we have the following objective function: $J(\mathbf{p}) = \xi^T \xi = \mathbf{b}^T\mathbf{b} - \mathbf{b}^T\mathbf{Ap} - \mathbf{p}^T\mathbf{A}^T\mathbf{b} + \mathbf{p}^T\mathbf{A}^T\mathbf{Ap}$. Deriving, and imposing the derivate equal to zero we have: $\frac{\partial J(\mathbf{p})}{\partial \mathbf{p}} = -2\mathbf{A}^T\mathbf{b} + 2\mathbf{A}^T\mathbf{Ap}$, so the solution of the LSmin problem is:

$$\hat{\mathbf{p}} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b} = \mathbf{A}^+\mathbf{b} \tag{2.5}$$

where $\mathbf{A}^+$ is the Moore-Penrose pseudoinverse matrix. To evaluate the localization estimation error, defined as the Euclidean distance between the estimated position and the real one, we introduce the ranging error over the estimated distances: $\epsilon = (\epsilon_1, \epsilon_2, ..., \epsilon_n)$, and we model the RSS fluctuations as Gaussian noise, that is $\epsilon_i \sim \mathcal{N}(0, \sigma_i^2)$. This assumption is verified in [23]. We can write $\hat{d}_i = d_i + \epsilon_i$, and substitute $\hat{d}_i$ in equation 2.4. Then we have:

$$\mathbf{b} = \begin{pmatrix} (d_1+\epsilon_1)^2 - (d_n+\epsilon_n)^2 - x_1^2 + x_n^2 - y_1^2 + y_n^2 \\ (d_2+\epsilon_2)^2 - (d_n+\epsilon_n)^2 - x_2^2 + x_n^2 - y_2^2 + y_n^2 \\ \vdots \\ (d_{n-1}+\epsilon_{n-1})^2 - (d_n+\epsilon_n)^2 - x_{n-1}^2 + x_n^2 - y_{n-1}^2 + y_n^2 \end{pmatrix}$$
$$= \begin{pmatrix} (d_1^2+\epsilon_1^2+2d_1\epsilon_1) - (d_n^2+\epsilon_n^2+2d_n\epsilon_n) - x_1^2 + x_n^2 - y_1^2 + y_n^2 \\ (d_2^2+\epsilon_2^2+2d_2\epsilon_2) - (d_n^2+\epsilon_n^2+2d_n\epsilon_n) - x_2^2 + x_n^2 - y_2^2 + y_n^2 \\ \vdots \\ (d_{n-1}^2+\epsilon_{n-1}^2+2d_{n-1}\epsilon_{n-1}) - (d_n^2+\epsilon_n^2+2d_n\epsilon_n) \\ -x_{n-1}^2 + x_n^2 - y_{n-1}^2 + y_n^2 \end{pmatrix} \tag{2.6}$$

If we define the vector $\mathbf{b}_{true}$, characterized by the true distances d_i, as:

$$\mathbf{b}_{true} = \begin{pmatrix} d_1^2 - d_n^2 - x_1^2 + x_n^2 - y_1^2 + y_n^2 \\ d_2^2 - d_n^2 - x_2^2 + x_n^2 - y_2^2 + y_n^2 \\ \vdots \\ d_{n-1}^2 - d_n^2 - x_{n-1}^2 + x_n^2 - y_{n-1}^2 + y_n^2 \end{pmatrix} \tag{2.7}$$

$\mathbf{b}$ can be rewritten as:

$$\mathbf{b} = \mathbf{b}_{true} + \begin{pmatrix} \epsilon_1^2 + 2d_1\epsilon_1 - \epsilon_n^2 - 2d_n\epsilon_n \\ \epsilon_2^2 + 2d_2\epsilon_2 - \epsilon_n^2 - 2d_n\epsilon_n \\ \vdots \\ \epsilon_{n-1}^2 + 2d_{n-1}\epsilon_{n-1} - \epsilon_n^2 - 2d_n\epsilon_n \end{pmatrix} \tag{2.8}$$

and the true position of the target $\mathbf{p}$ is $\mathbf{p} = \mathbf{A}^+\mathbf{b}_{true}$. Now we can examine the localization error e as the following:

$$\begin{aligned} e =& \|\hat{\mathbf{p}} - \mathbf{p}\| \\ =& \|\mathbf{A}^+\mathbf{b} - \mathbf{p}\| \\ =& \|\mathbf{p} - \mathbf{p} + \mathbf{A}^+\mathbf{m}\| \\ =& \|\mathbf{A}^+\mathbf{m}\| \end{aligned} \tag{2.9}$$

where $m_i = \epsilon_i^2 + 2d_i\epsilon_i - \epsilon_n^2 - 2d_n\epsilon_n$. By the definition of matrix norm:

$$\|\mathbf{A}^+\| = \max_{x \neq 0} \frac{\|\mathbf{A}^+\mathbf{x}\|}{\|\mathbf{x}\|} \tag{2.10}$$

we have:

$$\|\mathbf{A}^+\| \geqslant \frac{\|\mathbf{A}^+\mathbf{x}\|}{\|\mathbf{x}\|} \quad \longrightarrow \quad \|\mathbf{A}^+\mathbf{x}\| \leqslant \|\mathbf{A}^+\| \cdot \|\mathbf{x}\|$$

Let $\delta e_i = 2d_i\epsilon_i - 2d_n\epsilon_n$ and $\psi_i = \epsilon_i^2 - \epsilon_n^2$, that is $m_i = \delta e_i + \psi_i$, so we can write

$$\|\mathbf{A}^+\mathbf{m}\| \leqslant \|\mathbf{A}^+\| \cdot \|\mathbf{m}\| = \|\mathbf{A}^+\| \cdot \|\delta e + \psi\|$$

thanks to the triangular inequality:

$$e \leqslant \|\mathbf{A}^+\| \cdot \left(\|\delta e\| + \|\psi\|\right) \tag{2.11}$$

In [24] is proved that the matrix norm induced by the euclidean vector norm is:

$$\|\mathbf{A}^+\| = \frac{1}{\sqrt{\lambda_{min}}} \tag{2.12}$$

where λ_{min} is the smallest number λ such that $\mathbf{A}^\mathsf{T}\mathbf{A} - \lambda\mathbf{I}$ is singular. In other words λ_{min} is the smallest eigenvalue of the matrix $\mathbf{A}^\mathsf{T}\mathbf{A}$. From the equation 2.3 we have:

$$\mathbf{A}^\mathsf{T}\mathbf{A} = 4\begin{pmatrix} a & b \\ b & c \end{pmatrix} \tag{2.13}$$

where:

$$a = \sum_{i=1}^{n-1}(x_i - x_n)^2$$

$$b = \sum_{i=1}^{n-1}(x_i - x_n)(y_i - y_n)$$

$$c = \sum_{i=1}^{n-1}(y_i - y_n)^2$$

therefore:

$$\lambda_{min} = \frac{(a+c) - \sqrt{(a+c)^2 - 4(ac-b^2)}}{2} = \frac{(a+c-\sqrt{(a-c)^2+4b^2})}{2} \quad (2.14)$$

The upper bound expression

Finally we can write the **upper bound** for positioning error as:

$$e \leqslant \phi \cdot \gamma \quad (2.15)$$

It depends on two terms. Let analyze them and try to understand the upper bound behavior in function of some characteristic parameters. The graphics are all obtained by Matlab simulation considering, for the reasons explained in 2.3, a squared area (in this section $30 \times 30m^2$) with a variable number of APs placed according to a random uniform distribution inside it.

The first term: ϕ

The first term $\phi = \frac{1}{\sqrt{\lambda_{min}}}$, as evident by the equation 2.14, totally depends on the positions (x_i, y_i) of the reference access points and so it totally depends on topology. In a TVWS perspective we wonder: how does it change with the number of reference APs? The answer is *depicted* in Fig. 14: The value of the eigenvalue increase linearly with

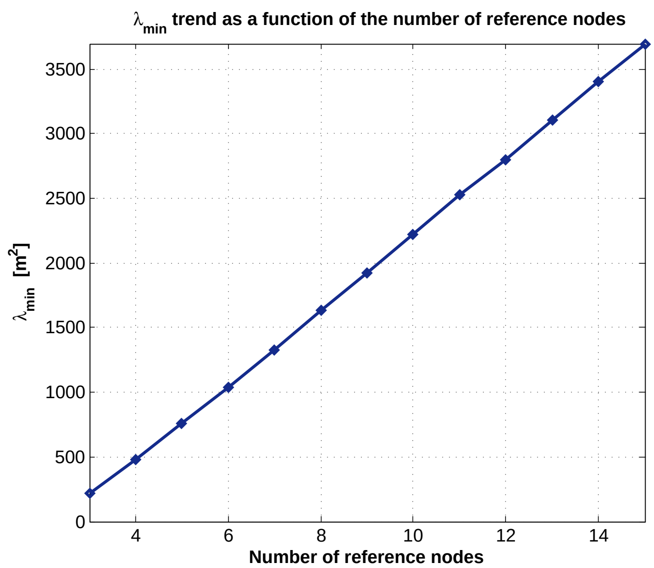


Figure 14: The λ_{min} trend with the increase of reference nodes number

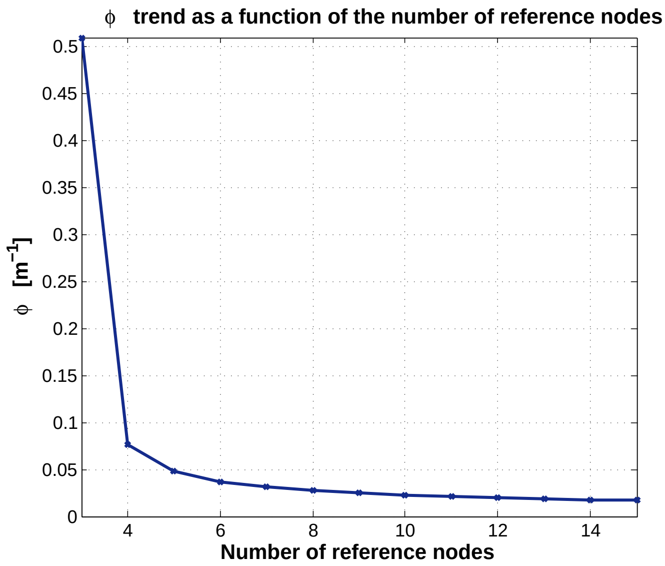


Figure 15: The ϕ trend with the increase of reference nodes number

the number of APs, so increasing the number of landmarks the value of ϕ decreases, as shown in Fig. 15.

The second term: γ

The second term $\gamma = \|\delta e\| + \|\psi\|$ depends on the statistical behavior of the two component δe and ψ. The ith component of δe is $\delta e_i = 2d_i\epsilon_i - 2d_n\epsilon_n$, thai is the difference of two random gaussian variable with zero mean and variance $2d_i\sigma_i^2$ and $2d_n\sigma_n^2$. The p.d.f of the difference between two random gaussian variables is given by the convolution of the two p.d.fs:

$$p_{\delta e_i}(\delta e_i) = p_{\epsilon_i}(\epsilon_i) * p_{\epsilon_n}(\epsilon_n)$$

The convolution between two gaussian p.d.fs is sitll a gaussian p.d.f with zero mean (in this case) and variance equal to the sum of variances: $\delta e_i \sim \mathcal{N}(0, \sigma_i'^2)$, where $\sigma_i'^2 = 2d_i\sigma_i^2 + 2d_n\sigma_n^2$. For simplicity let us consider the reasonable case where $\sigma_i = \sigma,\ i = 1, ..., n$. Therefore: $\psi_i = \sigma^2\psi_i' = \sigma^2(x_i^2 - x_n^2)$, with $x_i, x_n \sim \mathcal{N}(0, 1)$, this implies that $x_i^2, x_n^2 \sim \chi_1^2$, where χ_1^2 is the chi-squared distribution with order 1. Let $x_i^2 = z_i$, we have:

$$p_{\psi_i'}(\psi_i') = p_{z_i}(z_i) * p_{z_n}(z_n) \longrightarrow p_{\psi'}(\psi') = \mathcal{F}^{-1}\{C_{z_i}(u) \cdot C_{z_n}(-u)\}$$

Remembering that the moment generating function of the first order chi-squared distribution is:

$$M(jt) = \frac{1}{\sqrt{1-j2t}} \tag{2.16}$$

then:

$$\begin{aligned} C_{\psi'} =& C_{z_i}(u) \cdot C_{zn}(-u) \\ =& \frac{1}{\sqrt{1+j4\pi u}} \cdot \frac{1}{\sqrt{1-j4\pi u}} \\ =& \frac{1}{\sqrt{1-(j4\pi u)^2}} = \frac{1}{\sqrt{1+16\pi^2 u^2}} \end{aligned}$$

which is the Fourier transform of a modified Bessel function of the second kind of order zero. Remembering that:

$$\psi_i = \sigma^2 \psi_i' \quad \longrightarrow \quad p_{\psi_i}(\psi_i) = \frac{1}{|\sigma^2|} p_{\psi_i'}\left(\frac{\psi_i'}{\sigma^2}\right)$$

we finally obtain:

$$p_{\psi_i} = \frac{2}{a} \mathcal{K}_0 \left(\frac{2\pi}{a}|z|\right) \tag{2.17}$$

where $a^2 = 16\pi^2\sigma^4$. It has zero mean and variance $a^2/4\pi^2 = 4\sigma^4$. Then the second term γ strongly depends on the variance of the ranging error σ^2 but also on the distances between the target and the APs which contribute to the variance of δe. Increasing the number of reference nodes we expect that γ grows because with more nodes the scatter of the distances increases and so also the variance becomes bigger. This is shown in Fig.16: γ grows with the number of reference access points and with the ranging error variance σ.

In Fig. 17 and 18 is depicted the total trend of the upper bound in function of the number of reference APs, varying the value of σ^2. It increases when σ^2 increases but decreases when n increases.

Fig. 19 shows the localization error and the bound, both averaged over several iterations, which confirms that 2.15 is actually an upper bound for the positioning error.

In summary, from this model it is evident that the localization error critically depends on:

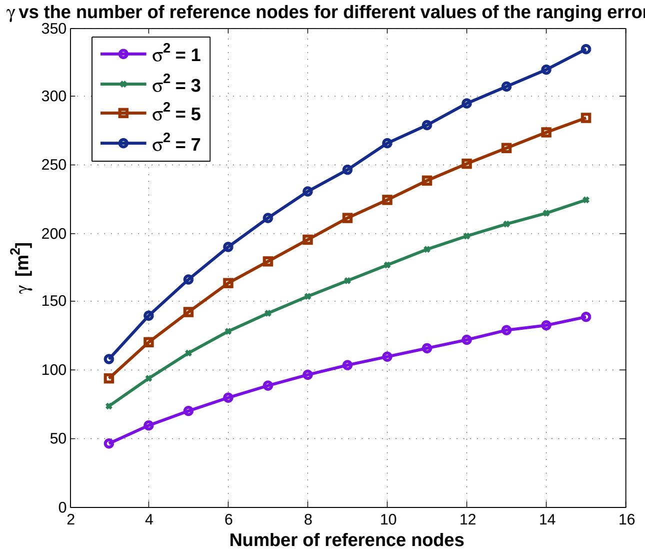


Figure 16: γ trend with the increase of reference nodes number, for different values of σ^2

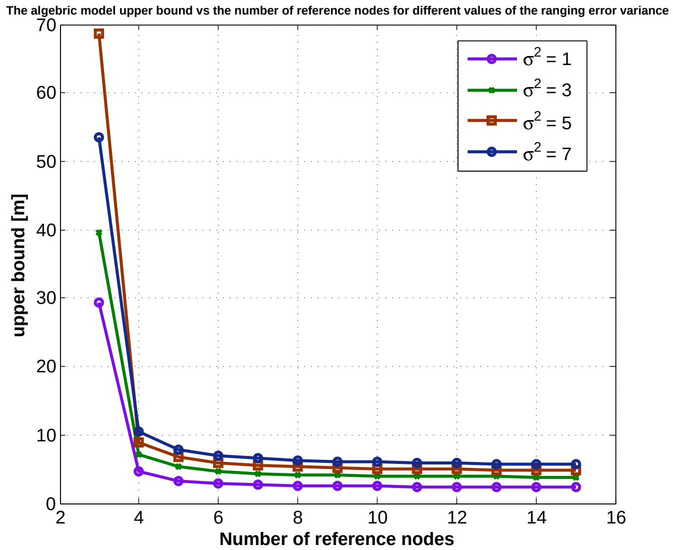


Figure 17: Upper bound in function of n, varying σ^2

- the number and topology of the landmarks
- the ranging error, in particular the ranging error variance

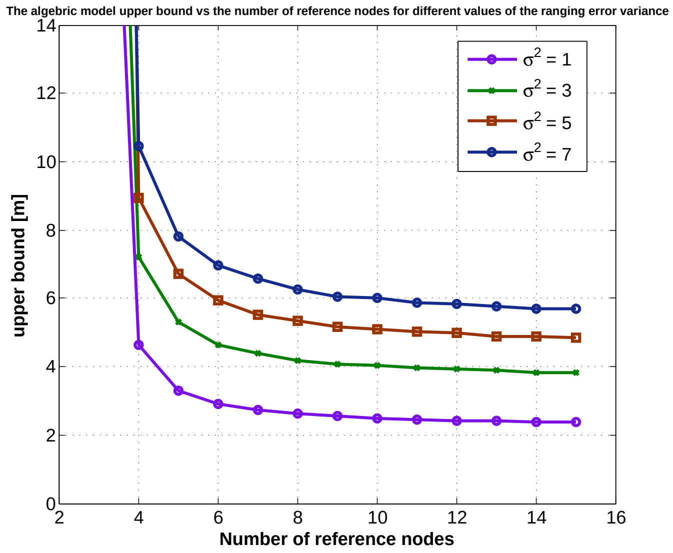


Figure 18: Upper bound in function of n, varying σ^2 (zoomed)

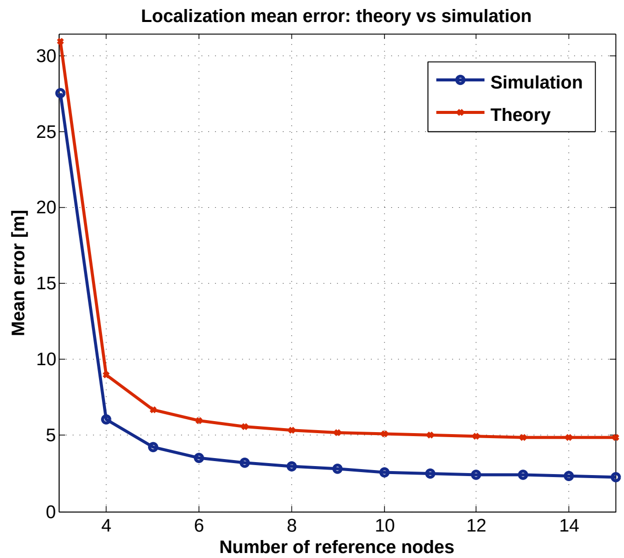


Figure 19: Theoretical upper bound vs simulated positioning error

2.2.2 *Model II: RSS uncertainty model*

In this section we develop a model for uncertainty of an RSS based localization system inspired by [25] and [26]. We develop this model in order to find a correspondence between the localization uncertainty (and so the error) and the limits of the RSS method, due to the fact that at any given location in a multi-path environment the received signal strength exhibits shadowing and so the signal strength fluctuates over time, regardless of simply algebraic consideration as made in the previous section. In this way we can verify if there are other parameters which influence the localization error specifically due to signals behavior.

Typically, in RSS approach, a signal strength vector $s(x, y) \in \mathcal{S}$, consisting of the received signal strengths from n different Access Points is associated with each location $(x, y) \in \mathcal{A}$, where $\mathcal{A}$ is the considered area. Using propagation models a mapping relationship $\mathcal{M} : \mathcal{A} \longrightarrow \mathcal{S}$ is generated: the location of the target is estimated by obtaining the signal strength vector at the target device and finding the closest matching vector from $\mathcal{M}$. Thanks to this mapping relationship we can map the uncertainty of the signal strength domain into the positioning plane one. Using the same terminology of the previous section, we say that the received signal strength vector at (x, y) is $s = (s_1, s_2, ..., s_n)$. The received signal strength s_i from the ith AP is a stochastic variable due to the effect of multipath propagation, it can be modeled as a normal distribution around a mean value $\bar{s}_i$ with a variance σ_i^2, so we have: $s_i = \bar{s}_i + \Delta s_i$, where $\Delta s_i \sim \mathcal{N}(0, \sigma_i^2)$. By dividing the signal strength into this two components we can consider the mapping from location to **mean** signal strength $\overline{\mathcal{M}} : \mathcal{A} \longrightarrow \overline{\mathcal{S}}$ and evaluate the effect of $\Delta\mathbf{s}$ on it. Moreover we make other reasonable hypothesis:

1. We assume that the mean signal strength $\bar{s}_i(x, y)$ at location (x, y) is a differentiable function over the region of interest and that the partial derivatives $\frac{\partial s_i}{\partial x}$ and $\frac{\partial s_i}{\partial y}$ are constant in the local neighborhood of (x, y). This means the signal is no subjected to strange propagation phenomena like distortions.

2. The components of $\mathbf{s}$ are independent, so the covariance matrix of $\Delta\mathbf{s}$ is given by: $\mathbf{C}_{\Delta s} = diag(\sigma_1^2, \sigma_2^2, ..., \sigma_n^2)$.

3. We consider a common exponential path loss model: the propagation loss is thus a monotonic function of the distance from the transmitter. In this case the mapping $\overline{\mathcal{M}}$ is a one-to-one (injective) function.

Under these assumptions we can calculate the uncertainty in signal space and than map it in location. To do this we define the *uncertainty region* $\mathcal{A}_\alpha \subseteq \mathcal{A}$, for $\alpha \in [0, 1]$ (which can be named as *degree of confidence*), as follows:

$$\int_{\mathcal{A}_\alpha} p\{\mathbf{s}|(x,y)\}dxdy = \alpha \tag{2.18}$$

that is: $\mathcal{A}_\alpha$ is a set of locations in $\mathcal{A}$ such that the probability that the observed signal strength vector is due to an AP located into a generic $(x, y) \in \mathcal{A}_\alpha$ is α. p is a p.d.f with support over $\mathcal{A}$.

Considering $\mathbf{s}' = \overline{M}(x, y)$ and $\mathcal{S}_\alpha = \overline{M}(\mathcal{A}_\alpha)$ and thanks to the properties 2 and 3 we can write:

$$\begin{aligned} \alpha &= \int_{\mathcal{A}_\alpha} p\{\mathbf{s}|(x,y)\}dxdy \\ &= \int_{\mathcal{S}_\alpha} q\{\mathbf{s}|\mathbf{s}'\}d\mathcal{S} \end{aligned} \tag{2.19}$$

Due to signal variance, the signal strength vector at a given location (x, y) is distributed, with a certain p.d.f, in a region centered around the mean signal strength vector $\bar{\mathbf{s}}$ at that location. Given α we can compute the characteristics of the hypervolume in the $n-$dimensional signal strength vector space having probability mass α and center $\bar{\mathbf{s}}$.

For simplicity of notation, only in this calculation, we write $\Delta\mathbf{s} = \mathbf{x}$. For the hypothesized joint p.d.f:

$$p_{\mathbf{X}}(\mathbf{x}) = \frac{1}{(\sqrt{2\pi})^2} e^{-\frac{1}{2}\mathbf{x}^T \mathbf{C}_x \mathbf{x}}$$

it is shown in [27] the hypervolume that contains a specified probability mass α is a hyperellipsoid of semi-axis $\sigma_i^2 R_n^2$, where R_n is the radius of a $n-$dimensional hypersphere containing the same probability mass. So, from equation 2.19 and hypothesis 2, we can write:

$$\alpha = \frac{1}{\prod_1^n \sigma_i (\sqrt{2\pi})^n} \int \cdots \int_{H_e} e^{-\sum_1^n x_i^2 / 2\sigma_i^2} dx_1 dx_2 ... dx_n \tag{2.20}$$

Where H_e is the hyperellipsoid defined by the equation:

$$\sum_{i=1}^{n} \frac{x_i^2}{\sigma_i^2} \leqslant R_n^2 \tag{2.21}$$

Performing the substitution $z_i = x_i/\sigma_i$ and simplifying, we obtain:

$$\alpha = \frac{1}{(\sqrt{2\pi})^n} \int \cdots \int_{H_s} e^{-\sum_1^n z^2/2} dz_1 dz_2 ... dz_n \tag{2.22}$$

with the hypersphere H_s defined by $\sum_{i=1}^{n} z_i^2 \leqslant R_n^2$. Moving to polar coordinates,

$$\begin{aligned} z_1 =& r \cos \phi_1 \\ z_2 =& r \sin \phi_1 \cos \phi_2 \\ &\vdots \\ z_{n-1} =& r \sin \phi_1 ... \sin \phi_{n-2} \cos \phi_{n-1} \\ z_n =& r \sin \phi_1 ... \sin \phi_{n-2} \sin \phi_{n-1} \end{aligned}$$

we have:

$$\begin{aligned} \alpha =& \frac{1}{(\sqrt{2\pi})^n} \int_0^{R_n} \int_0^{2\pi} \int_0^{\phi} \cdots \int_0^{\phi} e^{-\frac{r^2}{2}} r^{n-1} dr d\phi_1 \sin \phi_2 d\phi_2 ... \sin^{n-2} \phi_{n-1} d\phi_{n-1} \\ =& \frac{1}{(\sqrt{2\pi})^n} \int_0^{R_n} e^{-\frac{r^2}{2}} r^{n-1} dr \int_0^{2\pi} d\phi_1 \prod_{i=2}^{n-1} \int_0^{\pi} \sin^{i-1} \phi_i d\phi_i \\ =& \frac{1}{(\sqrt{\pi})^n} 2\pi M_{r,n} \prod_{i=2}^{n-1} N_i \\ =& \frac{2}{(\sqrt{\pi})^{n-2}} M_{r,n} \prod_{i=2}^{n-1} N_i \end{aligned} \tag{2.23}$$

Remembering the Gamma function $\Gamma(x)$, we have:

$$N_i = \int_0^{\phi} \sin^{i-1} \phi_i d\phi_i = \frac{\Gamma(\frac{i}{2})\Gamma(\frac{1}{2})}{\Gamma(\frac{i+1}{2})} = \frac{\Gamma(\frac{i}{2})}{\Gamma(\frac{i+1}{2})} \sqrt{\pi}$$

Which leads to

$$\begin{aligned}\prod_{i=2}^{n-1} N_i =&(\sqrt{\pi})^{n-2}\frac{\Gamma(\frac{n-1}{2})}{\Gamma(\frac{n}{2})}\frac{\Gamma(\frac{n-2}{2})}{\Gamma(\frac{n-1}{2})}\cdots\frac{\Gamma(1)}{\Gamma(\frac{3}{2})}\\ =&(\sqrt{\pi})^{n-2}\frac{\Gamma(1)}{\Gamma(\frac{n}{2})}\\ =&(\sqrt{\pi})^{n-2}\frac{1}{\Gamma(\frac{n}{2})}\end{aligned} \tag{2.24}$$

Finally, with the substitution $v = r^2/2$, we obtain:

$$\begin{aligned}M_{r,n} =&\frac{1}{(\sqrt{2})^2}\int_0^{\frac{R_n^2}{2}} e^{-v}(\sqrt{2})^{n-1}v^{\frac{n-1}{2}}(\sqrt{2})\frac{dv}{2\sqrt{v}}\\ =&\frac{1}{2}\int_0^{\frac{R_n^2}{2}} e^{-v}v^{\frac{n-2}{2}}dv\\ =&\frac{1}{2}\Gamma(\frac{R_n^2}{2},\frac{n}{2})\end{aligned} \tag{2.25}$$

Substituting 2.25 and 2.24 in 2.23:

$$\alpha = \Gamma_{inc}(\frac{R_n^2}{2},\frac{n}{2}) \tag{2.26}$$

where $\Gamma_{inc}(x, a)$ is the incomplete Gamma function. With this relationship we have characterized the uncertainty in the signal domain. To translate this uncertainty in the location domain we consider $\Delta p = (\Delta x \quad \Delta y)^T$, the vector of the change in location in the neighborhood of (x, y) and, similar, $\Delta s = (\Delta s_1 \Delta s_2 ... \Delta s_n)^T$ is the vector of signal strength variations around $\bar{\mathbf{s}}$. The relationship between these two vectors is given by:

$$\Delta \mathbf{s} = T\Delta \mathbf{p} \tag{2.27}$$

where $T = \{t_{ij}\}$, that is:

$$T = \begin{pmatrix} \frac{\partial \bar{s}_{11}}{\partial x} & \frac{\partial \bar{s}_{12}}{\partial y} \\ \frac{\partial \bar{s}_{21}}{\partial x} & \frac{\partial \bar{s}_{22}}{\partial y} \\ \vdots & \vdots \\ \frac{\partial \bar{s}_{n1}}{\partial x} & \frac{\partial \bar{s}_{n2}}{\partial y} \end{pmatrix}$$

is the Jacobian of the mapping $\overline{M}$. From 2.27, thanks to the hypothesis 1, we can write:

$$\Delta s_i = t_{i1}\Delta x + t_{i2}\Delta y, \quad i = 1, 2, ..., n. \tag{2.28}$$

We have found that the uncertainty region for a point (x, y) in signal strength domain is the hyperellipsoid centered in $\bar{\mathbf{s}}$ defined by the equation:

$$\sum_{i=1}^{n} \frac{\Delta s_i^2}{\sigma_i^2} = R_n^2 \tag{2.29}$$

Substituting 2.28 in 2.29:

$$\sum_{i=1}^{n} \frac{(t_{i1}\Delta x + t_{i2}\Delta y)^2}{\sigma_i^2} = R_n^2$$
$$\implies \left(\sum_{i=1}^{n} \frac{t_{i1}^2}{\sigma_i^2}\right)\Delta x^2 + \left(\sum_{i=1}^{n} \frac{t_{i2}^2}{\sigma_i^2}\right)\Delta y^2 + \left(\sum_{i=1}^{n} \frac{2t_{i1}t_{i2}}{\sigma_i^2}\right)\Delta x\Delta y - R_n^2 = 0$$

This is a quadratic in the (x, y)−plane of the canonical form $ax^2 + by^2 + cxy + d = 0$, where:

$$a = \sum_{i=1}^{n} \frac{t_{i1}^2}{\sigma_i^2} \;, \quad b = \sum_{i=1}^{n} \frac{t_{i2}^2}{\sigma_i^2} \;, \quad c = \sum_{i=1}^{n} \frac{2t_{i1}t_{i2}}{\sigma_i^2} \;, \quad d = -R_n^2 \tag{2.30}$$

To know what kind of curve it is we have to study the discriminant function $c^2 - 4ab$:

$$\begin{aligned}
c^2 - 4ab &= \left(\sum_{i=1}^{n} \frac{2t_{i1}t_{i2}}{\sigma_i^2}\right)^2 - 4\sum_{i=1}^{n} \frac{t_{i1}^2}{\sigma_i^2} \sum_{i=1}^{n} \frac{t_{i2}^2}{\sigma_i^2} \\
&= 4\left(\sum_{i=1}^{n} \frac{t_{i1}^2 t_{i2}^2}{\sigma_i^4} + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \frac{t_{i1}t_{i2}t_{j1}t_{j2}}{\sigma_i^2\sigma_j^2} - \sum_{i=1}^{n} \frac{t_{i1}^2 t_{i2}^2}{\sigma_i^4} - \sum_{i=1}^{n}\sum_{j=1, j\neq i}^{n} \frac{t_{i1}t_{i2}t_{j1}t_{j2}}{\sigma_i^2\sigma_j^2}\right) \\
&= 4\left(2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \frac{t_{i1}t_{i2}t_{j1}t_{j2}}{\sigma_i^2\sigma_j^2} - \sum_{i=1}^{n} \frac{t_{i2}^2}{\sigma_i^2}\right) \\
&= 4\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \frac{(-t_{i1}^2 t_{j2}^2 - t_{i2}^2 t_{j1}^2 + 2t_{i1}t_{i2}t_{j1}t_{j2})}{\sigma_i^2\sigma_j^2} \\
&= -4\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \frac{(t_{i1}t_{j2} - t_{i2}t_{j1})^2}{\sigma_i^2\sigma_j^2} \leqslant 0
\end{aligned}$$

The equality obtains she all the term of the form $(t_{i1}t_{j2} - t_{i2}t_{j1})$ vanish. In this case $t_{i1}/t_{i2} = \text{const}.\forall i$. This is a degenerate case where the APs are collinear. Excluding this case, $c^2 - 4ab < 0$, which indicates that the quadratic form is an ellipse. Remembering the geometric properties of the ellipse, we have found that **the uncertainty region in the location plane is an ellipse with semi-axis**:

$$r_{max,min} = \sqrt{\frac{-2d}{(a+b) \pm \sqrt{(a-b)^2 + c^2}}} \tag{2.31}$$

So the location estimation accuracy ellipse is described by the equaltion:

$$\frac{x^2}{r_{max}} + \frac{y^2}{r_{min}} = 1 \tag{2.32}$$

Relating uncertainty and error: CEP

Now we have a measure of the uncertainty, how is it possible to relate it to the mean location error? A possible way is to use Circular Error Probability (**CEP**). CEP is defined as the radius of a circle, centered about the mean, whose boundary is expected to include 50% of observation, as shown in Fig. 20. Considering an unbiased estimation the

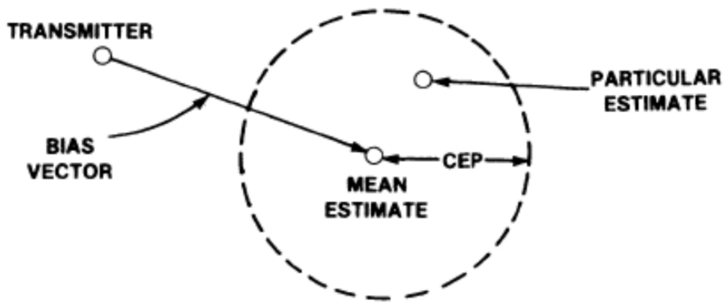


Figure 20: Circular Error Probability

center of this circle is the real position of the target, so we have that the CEP is an approximation for the positioning mean error. As shown in [28] the expression of the CEP is quite complex and depends on the ratio between the semi-axis of the ellipse β. Therefore a good approximation that is accurate to within approximately 10 percent for all values of β is:

$$\text{CEP} \approx 0.75\sqrt{c_1 + c_2} \tag{2.33}$$

where $c_1 = \frac{r_{max}^2}{\kappa}$ and $c_2 = \frac{r_{min}^2}{\kappa}$, with κ depends on the confidence level α and under the Gaussian hypothesis is $\kappa = -2\ln(1-\alpha)$.

To evaluate the CEP we first have to calculate the coefficients t_{i1} and t_{i2}. To do this we consider (as in further sections) a log-distance radio propagation model, so the mean signal strength $\bar{s}$ at a location (x, y) at a distance d from a radio source is given by:

$$\bar{s} = \bar{s}_0 - 10\gamma \log d$$

where $\bar{s}_0$ is the signal strength (measured in dBm) at the reference distance of 1 meter and γ is the path loss exponent. Assuming the same propagation constant for all the landmarks we have: $\bar{s}_i = \bar{s}_0 - 10\gamma \log d_i$, $i = 1, ...n$, with $d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$. From this we get:

$$t_{i1} = \frac{\partial \bar{s}_i}{\partial x} = \frac{-10\gamma(x - x_i)}{(x - x_i)^2 + (y - y_i)^2}$$
$$t_{i2} = \frac{\partial \bar{s}_i}{\partial y} = \frac{-10\gamma(y - y_i)}{(x - x_i)^2 + (y - y_i)^2} \tag{2.34}$$

Observations:

Now we can make several interesting observations about the CEP and its dependence on various parameters of the location estimation problem.

The confidence level α

The confidence level α influences the CEP indirectly through its effect on the factor R_n. We present the relationship between α and R_n for different values of the number of landmarks n in Fig.21. We notice that for a given value of α, R_n increases with increasing n. However this effect is countered by the other factors in 2.31.

Signal Variance

Let us consider the case where $\sigma_i = \sigma$, $i = 1, ..., n$. In this case extracting the common factor σ^2 in the definitions 2.30, we can see that the CEP is proportional to σ by using the equation 2.31. As expected the error in estimation reduces with reducing signal variance.

Landmarks relative distances

We investigate the dependence of CEP on the distance between APs by varying the considered area in which APs are distributed according to a uniform random distribution.

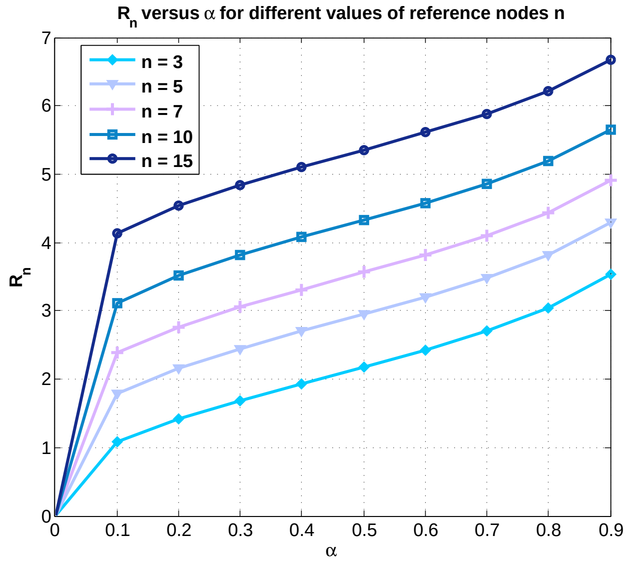


Figure 21: R_n vs α varying the value of n

In this way, after several iteration, the average distance between APs increase. From Fig. 22 we note that for a given value of the number of landmarks, the value of CEP increases by increasing the distance between APs.

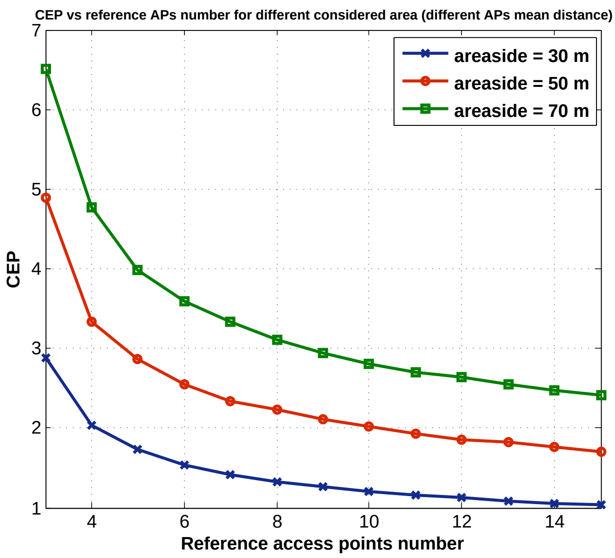


Figure 22: CEP vs number of landmarks, varying the areaside

Number of APs

If we consider more APs for a fixed area the CEP decreases, as we expected. This is shown in Fig. 23

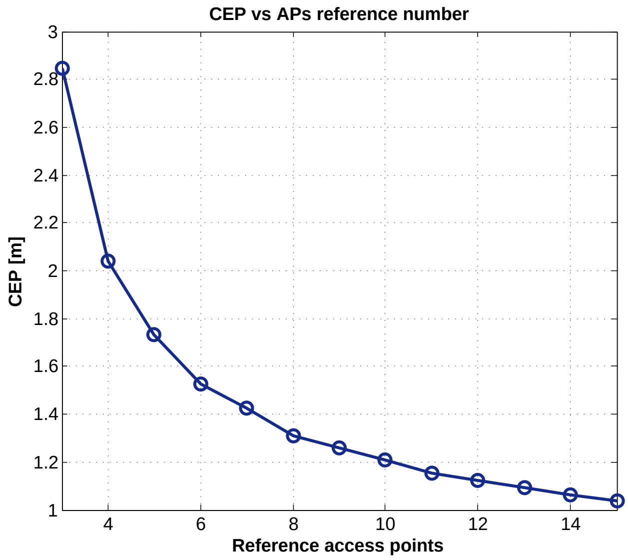


Figure 23: CEP vs the number of landmarks

Path Loss exponent

The most important dependence which arises by analyzing this model is that on the propagation constant. Equations 2.34 and 2.31 indicate that the accuracy increases with increasing γ, although the signal becomes weaker. This is explained by the fact that as γ increases, the signal level is more sensitive to location changes. That is: a large γ is given by a large propagation constant and this implies rapid change in signal strength over distance and hence a given variation in signal strength will correspond to a smaller distance than with a smaller propagation constant. This could be a problem in the evaluation of the possible advantages of using TV bands for positioning because in that case the operating frequencies (and so γ) are smaller than the WiFi ones and so we might expect a worse performance in term of localizetion error, despite the better propagation characteristics. In fact (luckily), as shown in Fig. 24, increasing the number of APs we obtain a better performance also when γ is much smaller.

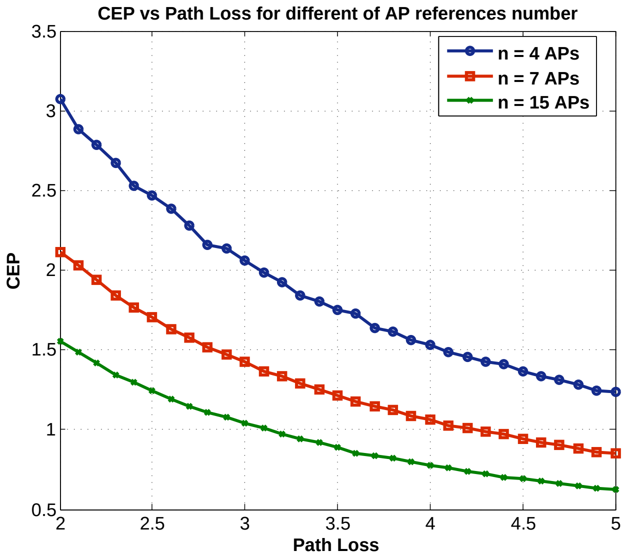


Figure 24: CEP vs γ, variyng n

2.3 TVWS VERSUS WIFI I: POSITIONING SYSTEMS

Wireless LAN (WLAN) operating in the ISM bands and using the IEEE 802.11x (i.e., standard WiFi technology) is one of the fastest and cheapest broadband wireless access systems, and has seen a high growth rate. Examples of deployment include WiFi hotspots, municipal WiFi networks and public WiFi networks, such as the wonderful BT-FON in the United Kingdom: with FON, residential broadband customers share a portion of their home WiFi broadband bandwidth for outdoor public use.

The rapid growth of the number of wireless access points in urban areas has brought forth the WiFi based positioning system (WPS) that can solve the positioning in certain situations (like indoors). Some providers like *Skyhook Wireless*, *Google* or *Fraunhofer Institute* maintains a public database that can be accessed through an API, and get the position based on the access points are accessible from a terminal (the AP location is associated with the MAC addess of that AP).

Unfortunately, despite the high density of access points available for WPS, the coverage provided by such WiFi networks is currently rather patchy. This is due to a combination of the relatively stringent regulatory caps on transmit power levels of WiFi in Europe, e.g., 20 dBm (100 mW) in the 2.4 GHz band and also due to the high wall and floor penetration loss suffered by signals in the ISM bands. By switching operation of the network from the ISM bands to TVWS spectrum, the above coverage limitations could be overcome. The architecture of the *hypothesized* network is shown in Fig. 25. This architecture is based on the use

Network architecture hypothesis

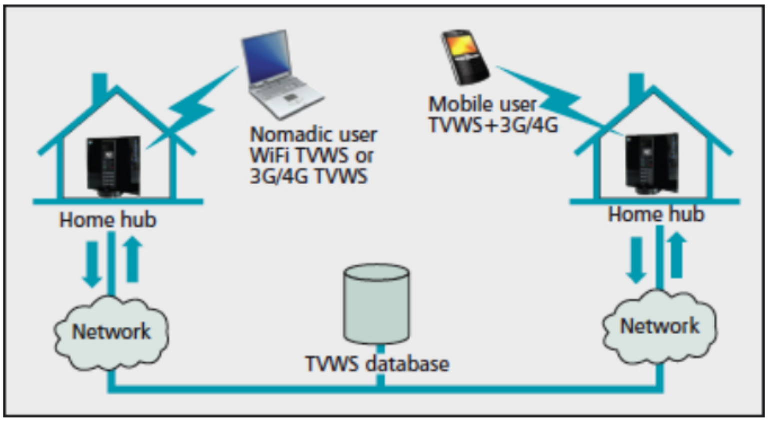


Figure 25: Network architecture using access points operating in TVWS.

of geo-location database. Each access point is assumed to be connected to one, or multiple, databases which provide information on the unused TVWS channels that are available at the location of the access point and information on maximum transmit power levels that could be used in each channel. Furthermore, the use of master-slave technology means that the necessary functionalities for database lookup and channel selection need to be implemented only in the access points, so keeping the complexity and cost of end-user devices to a minimum. Users with a TVWS modem, or dongle, can connect from outside to home access points via a TVWS channel that is periodically advertised via beacons by each access point. In [29] the problem of coverage was addressed. The main results are reported in Fig. 26,27 and 28: it can be seen that coverage is very patchy when the system operates at 5 GHz and some improvement is gained by switching to 2.4 GHz. The most striking result is achieved when home access points switch operation to TVWS.

Our purpose

From a TVWS-end user point of view this corresponds to an increase in range of transmission. In this way the device which is trying to establish its position by WPS can

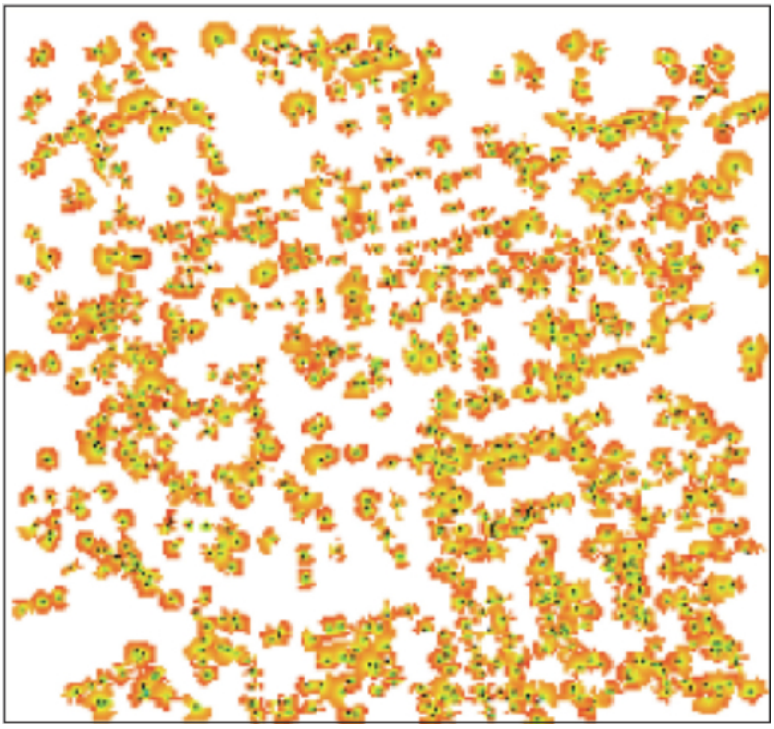


Figure 26: Achievable coverage using access points operating at 5 GHz

reach a greater number of access points. As shown in 2.2.1 and 2.2.2 , the positioning error depends, beyond various parameters, on the available number of access points. In particular positioning error decreases when the number of APs increases. This idea is depicted in Fig. 29 In this figure we suppose that the same device can operate at 2.4GHz , 790MHz and 490MHz (the outers of TV bands). It is evident that the range and the APs number obtained by the terminal operating in TV bands is much larger than that which works in the ISM one. Having said that we want to evaluate the possible advantages in using TVWS instead WiFi in positioning system. To do this we first have to choose an appropriate radio propagation model. A good compromise between simplicity and accuracy for an indoor-outdoor analysis is the widely used **Log-distance path loss model**, characterized by the following equation:

Radio propagation model

$$P_{LdB} = -27.55 + 20 \log f_{MHz} + 10\gamma \log d + X_g \qquad (2.35)$$

where:

- f_MHz is the carrier frequency expressed in MHz

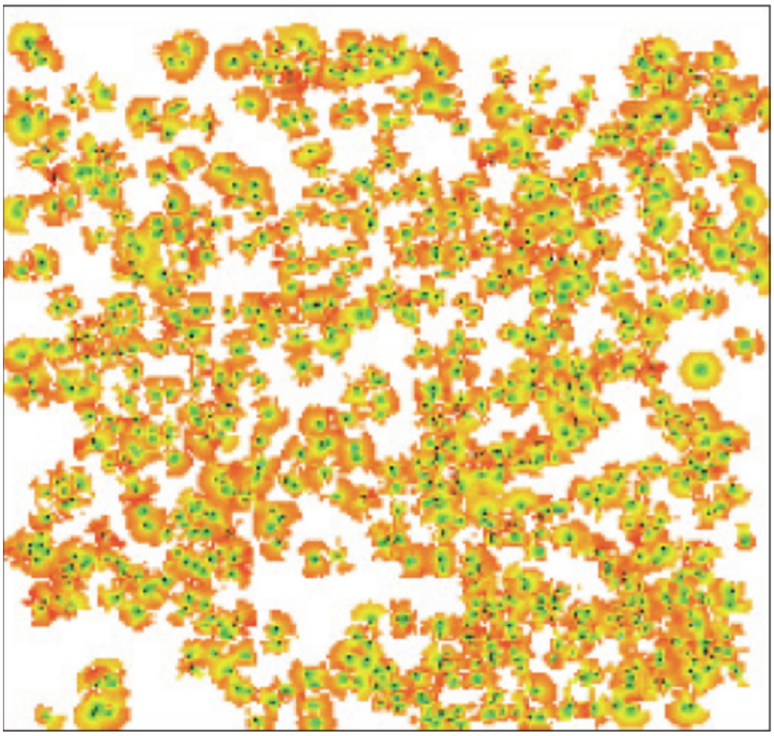


Figure 27: Achievable coverage using access points operating at 2.4 GHz

- γ is the path loss exponent, usually taken between 2 (= free space loss exponent) and 5 (dense urban)
- X_g is a random variable $\sim \mathcal{N}(0, \sigma^2)$ to take into account fading, cable and body losses

Network scenario

We consider an extended squared area, of area A, which represents for example an university campus, a factory and so on. In this a certain number of access points (N_{ap}) are distributed according to a random uniform distribution, therefore:

$$p_{X_i}(x_i) = \frac{1}{\sqrt{A}} \mathrm{rect}_{\sqrt{A}}(x_i - \frac{\sqrt{A}}{2}) \quad (2.36)$$

$$p_{Y_i}(y_i) = \frac{1}{\sqrt{A}} \mathrm{rect}_{\sqrt{A}}(y_i - \frac{\sqrt{A}}{2}) \quad (2.37)$$

An example is shown in Fig. 30.

Technology hypothesis

For the WiFi case we consider a classic 802.11/b system with 20MHz channel bandwidth and data rate 11Mb/s. For the TVWS, because a standard system does not exist today, we suppose that a *possible* 802.11/af is an 802.11/n based system. We consider the worst case: only one available TV

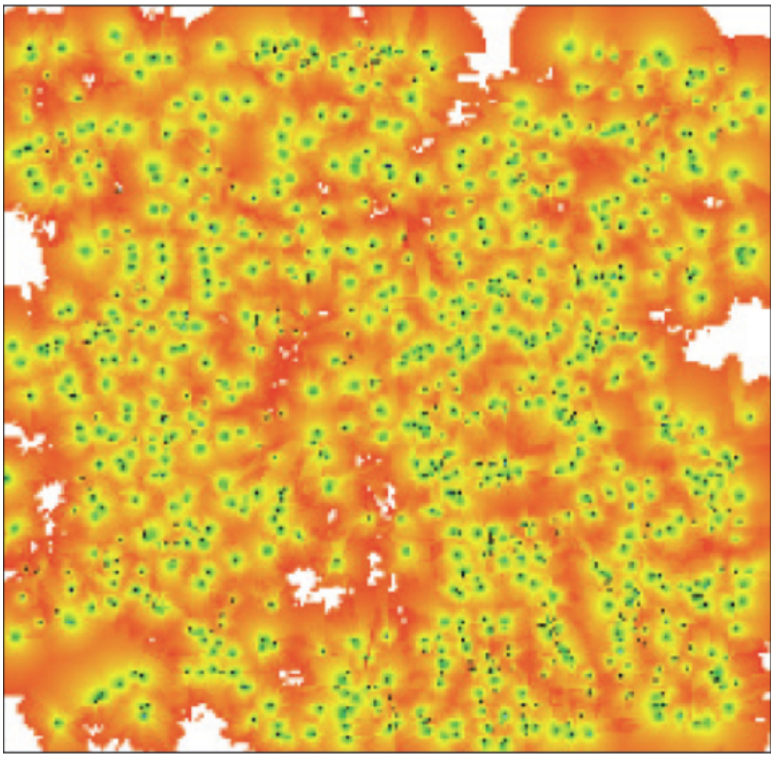


Figure 28: Achievable coverage using access points operating at TVWS frequencies

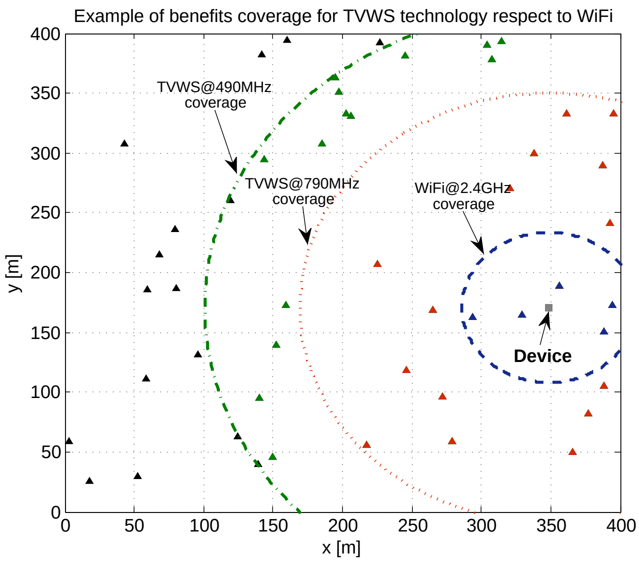


Figure 29: Transmission range and reached APs for WiFi and TVWS ($P_{tx} = 30dBm$, Log-distance path loss model)

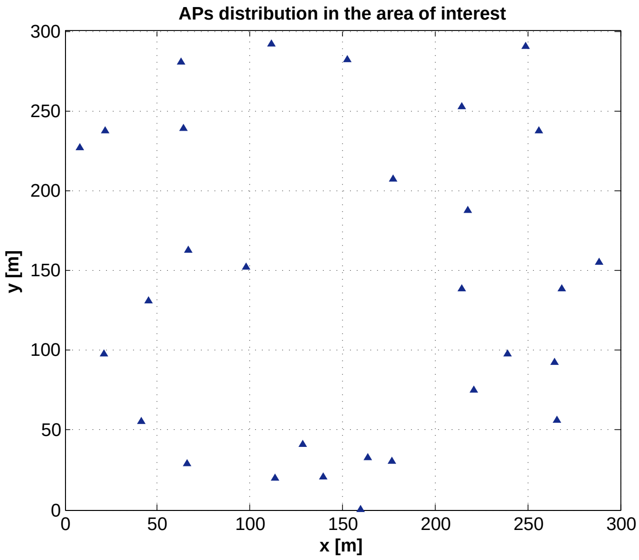


Figure 30: The considered network scenario

Table 1: Propagation model and network setup parameters

Parameters	Value
γ	3.2 (WiFi) - 3 (TVWS)
σ^2	6 dB
N_{ap}	30
$A(area)$	300 m^2

channel, so the channel bandwidth is $8MHz$, considering for example a $16QAM$ modulation scheme and a convolutional code with code rate of $\frac{1}{2}$ we obtain approximately $11Mb/s$ data rate. We suppose to use CISCO Aironet 350 access points, with a receiver sensitivity (for $f_b = 11Mb/s$) of $-82dBm$. All the parameters used in the simulation are summarized in Table 1 and 2.

Matlab simulations results are shown in Fig. 31 and 32. From Fig. 31 it is evident that, for the same transmitted power, the average number of APs reached by a TVWS device (both 470 and 790 MHz) is by far much greater than

Table 2: Technical choice for comparing the various spectral bands

Parameters	WiFi	TVWS
Radio frequency	2.4 GHz	470,790 MHz
EIRP	$14.77 \div 20 dBm$	$14.77 \div 20 dBm$
Channel Bandwidth	20 MHz	8 MHz
Receiver sensitivity	-82 dBm	-82 dBm

the WiFi one. For the special case network scenario the WiFi device is able to cover only a little more than 5 APs for its maximum transmitted power value when the TVWS one always reaches more than half of the total APs.

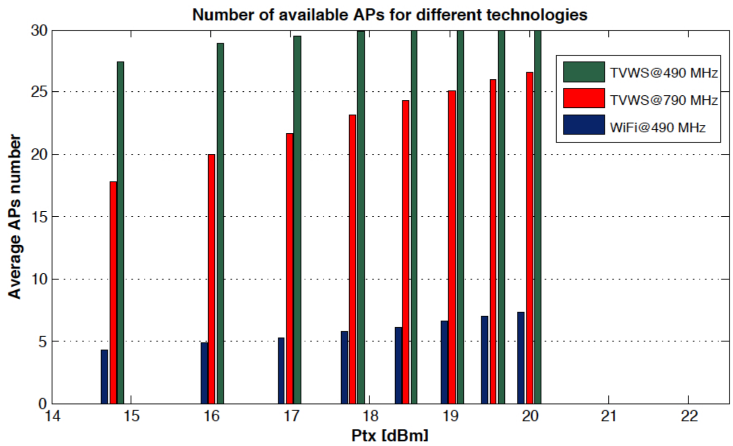


Figure 31: Number of reached APs for different spectral bands

This is reflected in localization performances, as shown in Fig 32, TVWS device strongly outperforms the WiFi one, obtaining a very small average error value also with the minimum transmitted power value considered: for $14.77 dBm$ average positioning error obtained by a TVWS-system is more than 6 meters below! The previous results raise our idea of a positioning system which is *green* in power. This means a system capable to offer the same performance of the existing ones by using less energy, which is a very attractive problem in modern communication systems. The simulation parameters are listed in Table 3 and 4. Simulations results are shown in Fig. 33 and 34. As expected, this time, the APs-reached average number of the two systems are quite similar, but the transmitted power scale is com-

Energy saving

pletely different. From Fig. 34 we can see that for the same value of the average localization error the power saving is on average 10dB, which is a very important saving. The average errors orders are the same while the WSD reaches

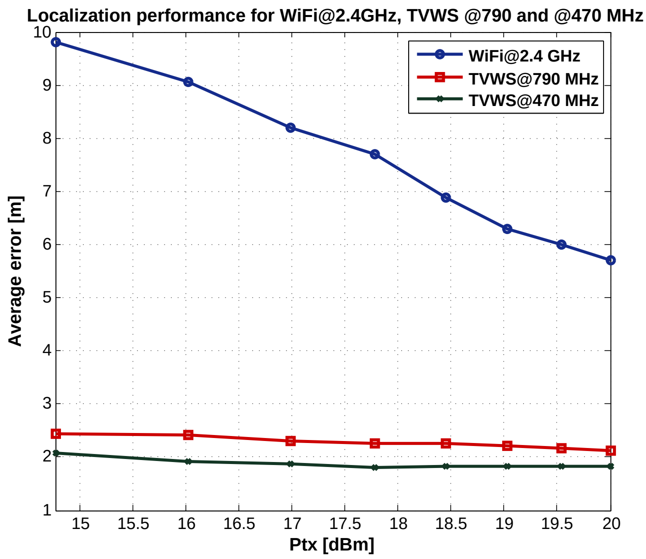


Figure 32: Average localization error vs transmitted power

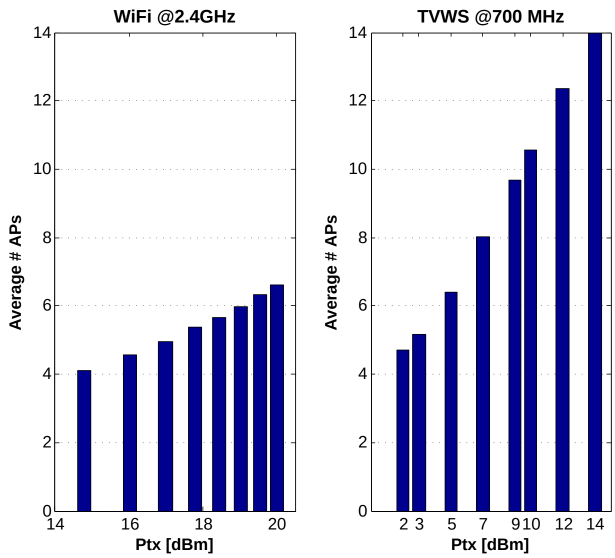


Figure 33: Average landmarks number for a WiFi system (on the left) and for a TVWS system (on the right)

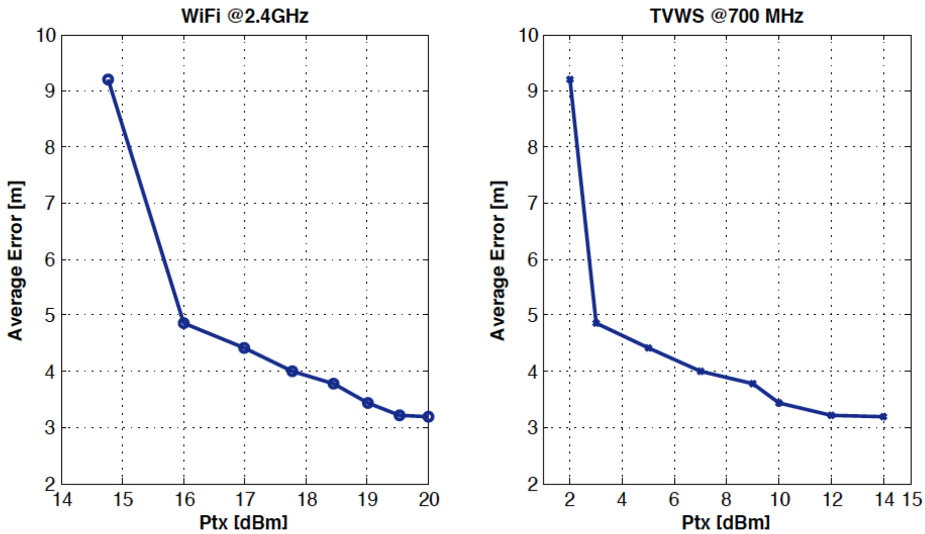


Figure 34: Average positioning error for a WiFi system (on the left) and for a TVWS system (on the right)

Table 3: Propagation model and network setup parameters 2

Parameters	Value
γ	3.2 (WiFi) - 3 (TVWS)
σ^2	6 dB
N_{ap}	15
$A(area)$	200 m^2

a greater number of reference nodes, because WiFi has a greater path loss exponent, as justified in 2.2.2 and in Figure 24

Table 4: Technical choice for comparing the two systems

Parameters	WiFi	TVWS
Radio frequency	2.4 GHz	700 MHz
EIRP	$14.77 \div 20dBm$	$2 \div 14dBm$
Channel Bandwidth	20 MHz	8 MHz
Receiver sensitivity	-82 dBm	-82 dBm

2.4 TVWS VERSUS WIFI II: HOME NETWORKING

In this section we evaluate the impact of a TVWS-framework for communication systems, in particular we focus on the evaluation of performances, in terms of downlink data rate, of using TV White Space spectrum for home networking services and compare them with that obtained by using the ISM WiFi.

WiFi 802.11n standard

One of the most common ways of creating a home network is by using wireless radio signal technology; the 802.11 network as certified by the IEEE. Most products that are wireless-capable operate at a frequency of 2.4 GHz under 802.11b and 802.11g or 5 GHz under 802.11a. Lately, most home networking devices operate in both radio-band signals using the standard 802.11n. This because this standard is particularly suitable in an environment full of reflections and others propagation phenomena which strongly influence channel conditions thanks to characteristics as OFDM modulation and MIMO antenna system, which provides a diversity gain thanks to a multipath condition. In this section we consider this standard for WiFi devices. IEEE 802.11n uses OFDM modulation with $N = 64$ subcarriers, 52 for data, 4 pilot subcarriers and 8 zero subcarriers(and so $N_u = 12$ "overhead" subcarriers); each of width $\Delta f = 0.3125MHz$, the guard time interval T_g is $800ns$. The same modulation and coding scheme (MCS) is used for each subcarrier, it varies with the signal strength level which arrives at the receiver to maintain a specified BER. In this section we consider a 2x1 diversity antenna scheme (and so only one spatial stream) and a $20MHz$ channel width, moreover we consider Cisco Aironet 1250 access point ([30]) which uses 64QAM,16QAM,QPSK and BPSK modulation with code rates $5/6, 3/4, 3/4, 1/2$, choosing the convenient scheme according to the received signal strength

Table 5: MCS and Sensitivity @2.4 GHz

Receiver sensitivity	MCS index
-86 dBm	MCS0
-85 dBm	MCS1
-84 dBm	MCS2
-83 dBm	MCS3
-80 dBm	MCS4
-75 dBm	MCS5
-74 dBm	MCS6
-73 dBm	MCS7

Table 6: MCS and Sensitivity @5 GHz

Receiver sensitivity	MCS index
-85 dBm	MCS0
-84 dBm	MCS1
-83 dBm	MCS2
-82 dBm	MCS3
-79 dBm	MCS4
-74 dBm	MCS5
-73 dBm	MCS6
-72 dBm	MCS7

(the receiver sensitivity varies for different MCS). It follows Table 5 for 2.4GHz and Table 6.

MCS-i is the modulation and coding scheme index, the associations are reported in Table 7.

TVWS "hypothesized" standard

For TVWS spectral band we assumed the same WiFi-OFDM technology, but we have to design it. The number of subcarrier N have to satisfy two constraints: for a given bandwidth B (that in our case is 20 MHz for WiFi and 8 MHz for TVWS single channel), to avoid "block fading"

Table 7: Modulation schemes and coding rates

MCS index	Code Rate	Modulation
MCS0	1/2	BPSK
MCS1	1/2	QPSK
MCS2	3/4	QPSK
MCS3	1/2	16-QAM
MCS4	3/4	16-QAM
MCS5	2/3	64-QAM
MCS6	3/4	64-QAM
MCS7	5/6	64-QAM

N must be such that $\frac{N}{B} < T_c$, where $T_c = \frac{c}{4\nu f_{carrier}}$ (ν is the mean speed of devices in meters per seconds) is the channel coherence time and such that the channel can be considered "flat": $N > \frac{B}{B_c} \approx \sigma_\tau B$, where B_c is the coherence bandwidth of the channel which can be approximate with the inverse of the delay spread σ_τ which, for an intense urban environment, is about 1μ s. So we have:

$$\sigma_\tau B < N < \frac{cB}{4\nu f_{carrier}}$$

For example, considering $f_{carrier} = 700MHz$ (TVWS band), $\sigma_\tau = 1\mu$ s, $\nu = 2m/s$ (the mean speed of a walking man inside the home) and $B = 8MHz$ we have: $8 < N < 6 * 10^4$. In this case we decide to maintain $\Delta f = 0.3125MHz$ so we have $N = \lceil B/\Delta f \rceil = 26$ subcarriers, which is an acceptable value with $N_u = 12$ and $T_g = 800ns$ again.

Propagation model

For home networking application we consider a radio propagation model more specific for indoor environment which is a modification of the COST231 Motley model (with isotropic antennas) (like in [31]):

$$PL_{indoor} = -27.55 + 20\log(f) + 10\gamma_{in}\log(d) + X_g + L_{wi}$$
$$PL_{indoor/outdoor} = -27.55 + 20\log(f) + 10\gamma_{wavg}\log(d) + X_g + L_{wi} + L_{wo}$$

where:

- γ_{in} is the indoor path loss exponent
- γ_{wavy} is the weighted averaged path loss exponent, weighted by the indoor distance and the outdoor distance: $\gamma_{wavy} = \frac{d_{in}\gamma_{in} + (d - d_{in})\gamma_{out}}{d}$

- $X_g \sim \mathcal{N}(0, \sigma_x^2)$ is a random variable to consider cable and body losses, fading and so on.
- L_{wi} and L_{wo} are inside and outside wall losses.

With this model we can calculate the received signal strength at the receiver for a given distance and select the right MCS (by Table 7). Then we evaluate the bit rate with the formula (see [32]):

$$f_b = \frac{c_R}{(1+\rho_G)(1+\rho_S)} B \log_2 L \quad (2.38)$$

where:

- c_R and L are the code rate and the number of modulation levels
- $\rho_G = T_G \Delta f$ is the temporal redundancy due to guard time
- $\rho_S = N_u/N$ is the inefficiency due to the lack of use of N_u subcarriers.

2.4.1 *Worst case: single TV channel*

The simulation provides results of a performance comparison study of expected data-rate versus range of a single hub-client pair for the three approaches considered. In this case we consider that only one TV channel is available (and so $B_{tvws} = 8\text{MHz}$). Moreover, for complexity reason and especially because we have no information about the future standard, we are only hypothesizing it, we consider no interference effects in order to set an upper bound for the chosen operating conditions. Using the information given in Table 8 and Table 9 and assumptions of earlier section, the data rate versus range performance for the various technologies is presented in Figure 35. As seen from the figure the highest possible bit rate achievable per home base station is mainly dependent upon both the modulation schemes supported and the channel bandwidth. So, because we hypothesized that their modulation schemes are the same, then at short distances from the home base station any difference in bit rate between them simply reflects the use of different radio frequency bandwidth channels. As a matter of fact the WiFi

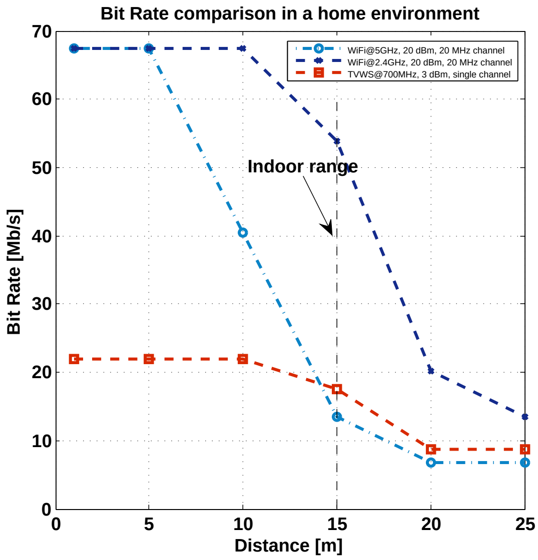


Figure 35: Data rate versus range comparison in varoius spectral bands

with 20MHz channel width has a peak bit rate of about 65Mb/s (MCS of index 7, for a single spatial stream), better than TVWS spectrum with 8MHz width with peak bit rate of around 22Mb/s. However, we can observe that WiFi at 5GHz has the greatest decrease in bit rate increasing distance, while TVWS band the least and the WiFi at 2.4GHz in between because their channel path loss is strongly influenced by the operating frequency. TVWS band performance starts to become comparable to that of WiFi at 5GHz at 14 meters and above and to that of WiFi at 2.4GHz at 20 meters and above. However, and more important, thanks to the improved propagation characteristics of lower frequencies TVWS band can provide a good indoor bit rate at a lower energy level respect to WiFi, that is 17 dB below!

2.4.2 *Spectrum aggregation case*

To match the peak bit rate performance of WiFi at 2.4 and 5 GHz , TVWS devices have two possible approaches: they could employ either more TV channels (if they are available)

Table 8: Propagation characteristics

Parameter	WiFi@5GHz	WiFi@2.4GHz	TVWS@700MHz
γ_{in}	4.4	4.3	4
γ_{out}	3.3	3.1	3
σ_x^2[dB]	10	10	10
L_{wo}[dB]	9	7	4
L_{wi}[dB]	5	4	1.5

Table 9: Technical choices for comparing the various spectral bands

Parameter	WiFi@5GHz	WiFi@2.4GHz	TVWS@700MHz
EIRP	20 dBm	20 dBm	3 dBm
Channel bandwidth	20 MHz	20 MHz	8 MHz
Wireless Interface	OFDM	OFDM	OFDM
Subcarriers n_i	64	64	26
Subcarrier width	0.3125 MHz	0.3125 MHz	0.3125 MHz

or increase in transmission power. The former is a very critical point because while the ISM bands are a contiguous chunk of spectrum, UHF white spaces are fragmented due to the presence of incumbents. The size of each fragment can vary from 1 channel of $8MHz$ (for Europe, $6MHz$ for USA). The amount of fragmentation in the UHF bands depends to a large extent on the density of TV stations, which varies considerably with population density. This is explained in Figure 36 (taken from [21]) which shows a histogram of an estimation of the contiguous spectrum widths that will be available after the DTV transition in US in three different area settings: urban, sub-urban and rural. As shown, the availability of more than two contiguous channels is very low for urban areas. However TVWS device could employ the use of spectrum aggregation technique such as DOFDM (Discontiguous OFDM), in which some multiple of OFDM subcarriers are aligned with the spacing of the existing channel plan; it is then possible to transmit on vacant channels and avoid active ones by placing data and zeros in the appropriate IFFT bins. So it is possible to have discontiguous spectrum use by means of multiple, independent carriers.

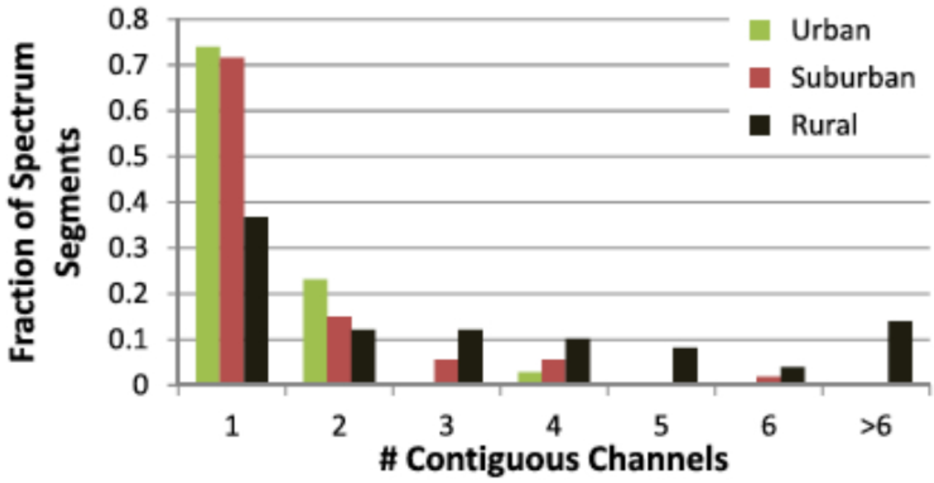


Figure 36: Channel fragmentation

The results using the two above mentioned approaches are

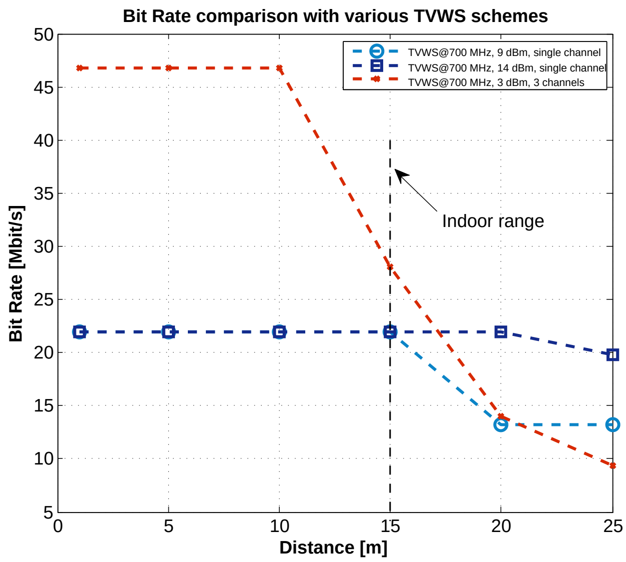


Figure 37: Data range versus range comparison using a combination of channel, power schemes in the TVWS band

shown in Figure 37 (using parameters given in Table 10 an Table 11). It is evident that the approach of increasing power levels does not bring significant improvements in data rates. This is because the system becomes capacity-limited for the given channel bandwidth (that is the channel bandwidth becomes the bottleneck of the system). On the

Table 10: Propagation characteristics

Parameter	TVWS (all configuration)
γ_{in}	4
γ_{out}	3
σ_x^2[dB]	10
L_{wo}[dB]	4
L_{wi}[dB]	1.5

Table 11: Technical choices for comparing the various spectral bands

Parameter	TVWS 1	TVWS 2	TVWS 3
Radio Frequency	700 MHz	700 MHz	700 MHz
EIRP	9 dBm	14 dBm	3 dBm
Channel bandwidth	8 MHz	8 MHz	24 MHz (channel bonding)
Wireless Interface	OFDM	OFDM	DOFDM
Subcarriers n¡	26	26	78
Subcarrier width	0.3125 MHz	0.3125 MHz	0.3125 MHz

other hand with a sufficient availability of the spectrum and with support of cognitive radio technology we can combine, for example, three channels to triple the effective data rate without substantial loss in range with only 3 dBm, that is a very low power level.

3 ANALYSIS ON CONSTRAINED TOPOLOGIES

In the previous chapter we found our results focusing the attention on a "free" topology, that is a topology in which the reference nodes are deployed in a random way inside the considered area in order to simulate real situations like a university, a campus or simply a residential quarter. In this chapter we consider constrained topologies, that is topologies which follows a fixed deployment structure in order to evaluate to possible advantages. We consider five types of topology:

1. **Random**: the topology used in the previous chapter, to make a comparison.

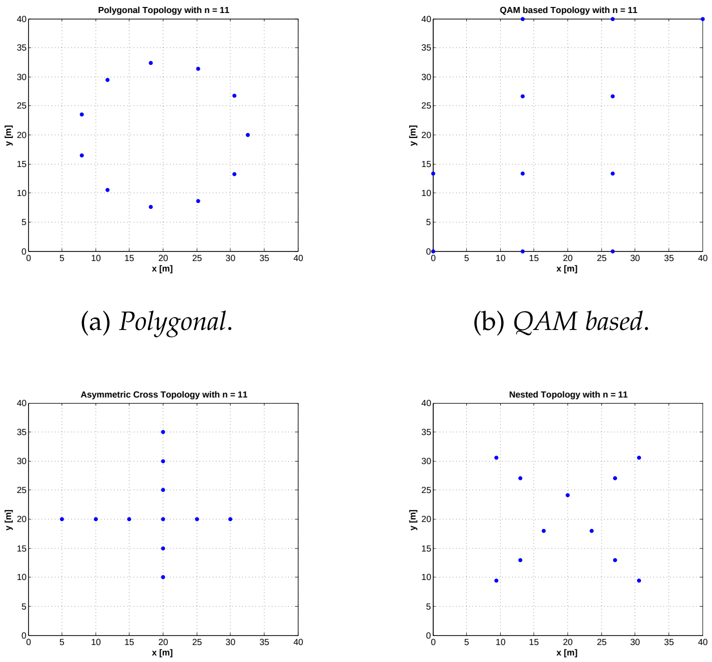
2. **Polygonal**: n nodes are distributed on the vertexes of a polygon inscribed in a circumference of radius which depends on the number of nodes and the (fixed) distance (called s) among nodes.

3. **QAM based**: n nodes are distributed on a QAM constellation which is limited by the entire considered area. If n is not a power of 2 we consider the next power of 2 (M) and we take away from the M-QAM constellation the $M - n$ exceeding nodes.

4. **Asymmetric cross**: n nodes are equally spatial (with distance s) distributed on an horizontal line and on a vertical one, similar to the shape of a cross.

5. **Nested**: based on the number of nodes n, this topology is composed by nested squares, and/or triangles, and/or a single central point. The distances among nodes are proportional to the nesting degree.

In Figure 38 is given an example of these topologies for $n = 11$. When we talk about constrained topology we refer to real situations such as an indoor environment in which we can organize the nodes with a fixed structure (for example to allow the localization of product in a supermarket) or a big factory which has a plan about network deployment.



(a) *Polygonal*. (b) *QAM based*.

(c) *Asymmetric Cross*. (d) *Nested*.

Figure 38: Example of topologies with $n = 11$

Table 12: Deployment parameters

Parameters	Value
N_{ap}	3:16
$A(area)$	100 m^2
s	8 m

These situations are not very interesting from a white spaces point of view because they consider small scenarios in which we can't exploit the advantages of the better radio propagation characteristics of the TV bands. However we have developed the algebraic model in 2.2.1 which gives an upper bound of the estimation error which depends on the smallest eigenvalue of the coordinates matrix, so we can gain an insight into the estimation error of different topologies only studying this eigenvalue, aside from the noise. With the parameters in Table 12 we obtain the result shown in Figure 39.

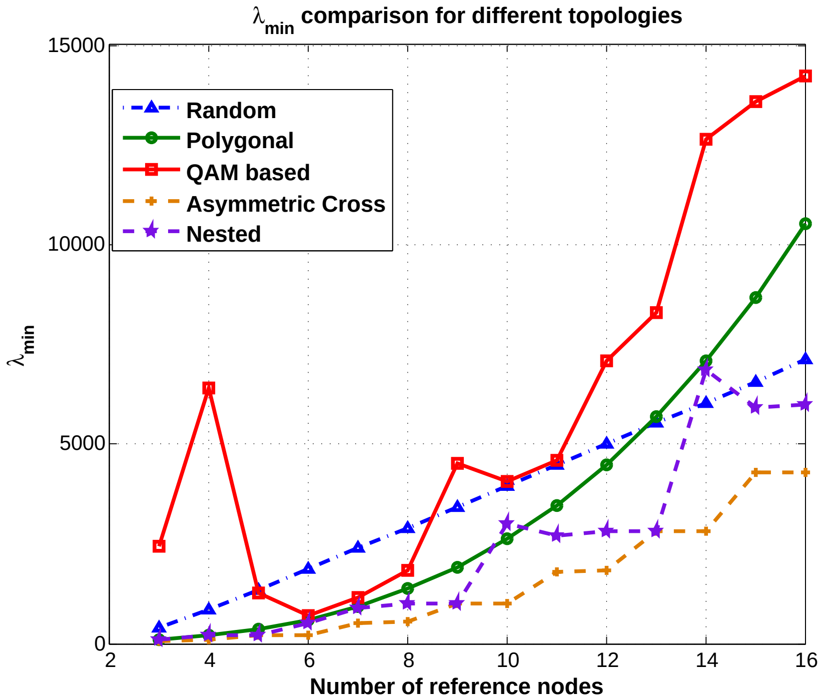


Figure 39: Pattern of the smallest eigenvalue of the coordinates matrix for different topologies

The figure shows that the general trend is the higher the number of nodes the higher value of the eigenvalue, even if the trend is irregular for the nested topology and the QAM based one. We notice that only the QAM topology outperforms the random one for the most values of the reference nodes number while the nested and the polygonal have an higher eigenvalue only for high values of n ($n > 14$). The asymmetric cross topology goes always worse. It is important to notice that the QAM based topology presents a very high value of the eigenvalue for $n = 4$. This depends on the fact that, even if the number of nodes is low, they have the maximum distance among them (equal to the $areaside = \sqrt{A}$). In this way the elements of the coordinates matrix are very spread.

How does the topology influence the upper bound trend? This is shown in Figure 40 which is obtained with the parameters in Table 12 and with a ranging error variance $\sigma_r^2 = 5$, The figure confirms that the QAM based, the nested and the polygonal topologies outperform the random one

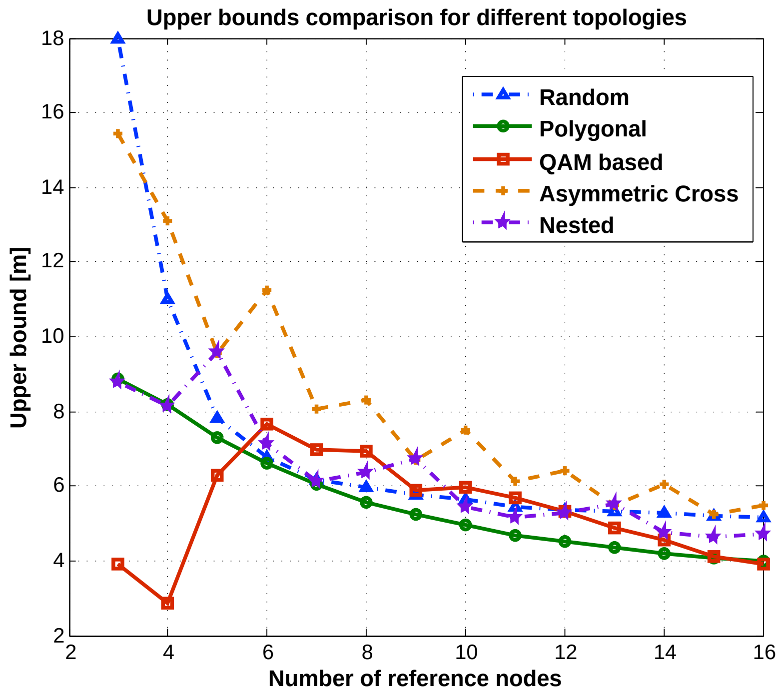


Figure 40: Pattern of the upper bound for different topologies

while the asymmetric cross goes worse. As seen before, it is curious the fact that for $n = 4$ the QAM based topology has a low peak, lower also than the value for greater number of nodes. This happen because, as seen before, the value of the eigenvalue is very high thanks to the coordinates matrix spread so the term ϕ of the expression 2.15 is low. In the same time also the term γ of the 2.15 is low because the number of reference nodes is low (see Figure 16). It follows that the value of the upper bound is very low.

In conclusion, if we can choose a fixed deployment structure for the reference nodes, we should choose a structure characterized by simply symmetry shapes like squares, triangles or polygons. Future works can study topology that maximize the spread of the coordinates matrix elements in order to maximize the eigenvalue and obtain in this way a lower upper bound. Moreover further studies about the noise should be made in order to choose a topology which minimize the effect of the ranging noise effect.

Part III

CONCLUSION AND APPENDIX

4 CONCLUSIONS

In this thesis we have analyzed the meaning of the expression "TV white spaces", the origin of these free frequency bands and the reasons of their arrival. We have highlighted as they can represent a very important resource for the future of communications. As a matter of fact we have seen that a regulatory framework for secondary utilization of TV white spaces is well underway in both the United States and the United Kingdom, while important steps in this direction are being taken within the European Union and elsewhere. We have also analyzed the current standardization to allow cognitive access to the white spaces in these countries. In particular, cognitive access to TVWS is a significant new opportunity for operators to provide a range of improved and new wireless services. We have introduced the two most common techniques which allow the access to the TVWS: spectrum sensing and the geo-location database approach. There are a lot of hard technical challenges for both the techniques (for example the evaluation of detection threshold for spectrum sensing and the management of the database for the geo-location) which determine the need of further studies and so a lot of investment on the research.

Then we have illustrated that applications that could benefit from white spaces operation is certainly WiFi at TV frequencies. Many industries like Google (WiFi on steroids), Microsoft (WhiteFi) or associations like IEEE (with the 802.11af, which is only a project proposal now) are developing systems or standards to use WiFi at TV frequencies. So we have tried to provide some elements to support the efforts of the research, in particular we have tried to highlight the possible advantages of using TVWS band instead of the ISM one for WiFi applications focusing our attention on WPS (WiFi based positioning system) and home networking. The main results are two:

The first is related to the coverage of WiFi at TV bands. Thanks to the better propagation characteristics of lower frequencies the transmission range of a WSD (White Space Device) is greater than that of the classic WiFi one. This could allow total coverage for internet access in urban areas or internet access in rural areas; but, especially, this could make a WSD able to reach a large number of WSAP (White Spaces Access Point), and this point is very important for positioning system. As a matter of fact we have developed two theoretical models for the positioning error and accuracy and they strongly depends on the number of access points reached, which are used as reference nodes from the positioning algorithms. In particular we have the greater the number of access points reached the lower the mean positioning error and the accuracy of RSS system. We found that the WiFi @ 2.4 GHz and the WiFi at TV bands (700 MHz) have the same mean error order but WSD uses less power level. So we have an important energy saving (on average 10 dB) by using TV bands instead the ISM one.

The second one concerns the WiFi at TV bands for home networking. WSD performance in terms of bit rate with a single available TV channel starts to become comparable to that of WiFi at 5GHz at 14 meters and above and to that of WiFi at 2.4GHz at 20 meters and above. However, and more important, thanks to the improved propagation characteristics of lower frequencies TVWS band can provide a good indoor bit rate at a lower energy level respect to WiFi, we can achieve an energy saving of around 17 dB. A better bit rate can be reached by using a very accurate cognitive radio technique and a spectrum aggregation technique because they could allow the employment of more available TV channels. As a matter or fact the channel bandwidth becomes the bottleneck of the system and if we combine, for example, three channels we triple the effective data rate without substantial loss in range with only 3 dBm, that is a very low power level.

A MATLAB CODE

In this section we account only the matlab functions used, we avoid to account the matlab scripts to not excessively weigh down the reading.

```
%This function calculates the bit rate of the OFDM modulation
    system, on
%which is based the 802.11n. We make these assumptions:
%GI = guard interval of 800 ns
%N = total subcarriers, 63 for the 802.11n (52 data, 4 pilots, 7
    guards)

function R = bitRateOFDM(B,codeRate,L)

deltaf = 0.3125; %[Mhz - subcarriers width]
N = ceil(B/deltaf);
Nu = 12;
GI = 800e-9;
B1 = B*1e6;

roG = GI*(B1/N); %temporal redundancy introduced by the time
    guard interval
roS = Nu/N; %inefficiency due to the unused subcarriers

R = (codeRate*B*log2(L))/((1+roG)*(1+roS)); %[Mb/s]


%This function chooses the code and modulation scheme of an OFDM
    subcarrier
%from the received power (dBm), these associations are related
    to a Cisco
%AIRONET 1250 Access Point [ref] for 802.11n.

%INPUT:
%PrxdBm = is the received power at the access point
%flag = 0 for TVWS and WiFi @ 2.4 GHz, 1 for WiFi @ 5Ghz
%OUTPUTS:
%R = is the code rate (usually convolutional codes)
%L = is the number of level of the modulation scheme

function [R,L] = chooseMCS(PrxdBm,flag)

switch flag
    case 0
        if (PrxdBm >= -73)
            %MCS-7
            R = 5/6;
            L = 64;

        elseif((PrxdBm < -73)&&(PrxdBm >= -74))
            %MCS-6
            R = 3/4;
            L = 64;

        elseif((PrxdBm < -74)&&(PrxdBm >= -75))
            %MCS-5
            R = 2/3;
            L = 64;
```

```
        elseif((PrxdBm < -75)&&(PrxdBm >= -80))
            %MCS-4
            R = 3/4;
            L = 16;

        elseif((PrxdBm < -80)&&(PrxdBm >= -83))
            %MCS-3
            R = 1/2;
            L = 16;

        elseif((PrxdBm < -83)&&(PrxdBm >= -84))
            %MCS-2
            R = 3/4;
            L = 4;

        elseif((PrxdBm < -84)&&(PrxdBm >= -85))
            %MCS-1
            R = 1/2;
            L = 4;

        elseif((PrxdBm < -85)&&(PrxdBm >= -86))
            %MCS-0
            R = 1/2;
            L = 2;

        elseif(PrxdBm < -86)
            %Too far away
            R = 1/2;
            L = 2;
            warning('Too far away!')
        end

    case 1
        if (PrxdBm >= -72)
            %MCS-7
            R = 5/6;
            L = 64;

        elseif((PrxdBm < -72)&&(PrxdBm >= -73))
            %MCS-6
            R = 3/4;
            L = 64;

        elseif((PrxdBm < -73)&&(PrxdBm >= -74))
            %MCS-5
            R = 2/3;
            L = 64;

        elseif((PrxdBm < -74)&&(PrxdBm >= -79))
            %MCS-4
            R = 3/4;
            L = 16;

        elseif((PrxdBm < -79)&&(PrxdBm >= -82))
            %MCS-3
            R = 1/2;
            L = 16;

        elseif((PrxdBm < -82)&&(PrxdBm >= -83))
            %MCS-2
            R = 3/4;
            L = 4;

        elseif((PrxdBm < -83)&&(PrxdBm >= -84))
            %MCS-1
            R = 1/2;
```

```matlab
            L = 4;

        elseif((PrxdBm < -84)&&(PrxdBm >= -85))
            %MCS-0
            R = 1/2;
            L = 2;

        elseif(PrxdBm < -85)
            %Too far away
            R = 1/2;
            L = 2;
            warning('Too far away!')
        end
end

end



%This function calculates the localization error, due to a Gaussian ranging
%error, on the LS estimates.

function [LSerror,A,b] = LSestimation(APcoords,MScoords,distances,lendmarks,sigma2)

%lendmarks = is a vector which contains the index of the AP considered as
%reference nodes
%sigma2 = variance of the Gaussian noise

N = length(lendmarks);

if(N>size(APcoords,1))
    error('Not possible to have more lendmarks than nodes!');
end

awgn = sqrt(sigma2).*rand(1,length(distances));
badDist = distances + awgn';

%Construction of the A matrix of the linear problem:
A = zeros(N-1,2);
for i=1:(N-1)
    A(i,1) = APcoords(lendmarks(i),1) - APcoords(lendmarks(N),1);
    A(i,2) = APcoords(lendmarks(i),2) - APcoords(lendmarks(N),2);
end
A = -2*A;

%Construction of the b vector
b=zeros(1,N-1);
for i=1:(N-1)
    b(i)=badDist(lendmarks(i))^2 - badDist(lendmarks(N))^2 - ...
        APcoords(lendmarks(i),1)^2 + APcoords(lendmarks(N),1)^2 - ...
        APcoords(lendmarks(i),2)^2 + APcoords(lendmarks(N),2)^2;
end

%Position estimates:
posMS = zeros(1,2);
posMS = posMS';
posMS = pinv(A)*b';

LSerror = sqrt((MScoords(1) - posMS(1))^2 + (MScoords(2) - posMS(2))^2);

```

```
%This function executes the lateration algorithm
function [error,A] = LSlateration2(APcoords,target,distances,ref
        ,sigma2)

N = length(distances);
errDist = distances + sqrt(sigma2)*randn(N,1);
xap = APcoords(:,1);
yap = APcoords(:,2);
xt = target(1);
yt = target(2);

k = length(ref);
A = zeros(k-1,2);
for i=1:(k-1)
    A(i,1) = xap(ref(i)) - xap(ref(k));
    A(i,2) = yap(ref(i)) - yap(ref(k));
end
A = -2*A;

b = zeros(k-1,1);
for i=1:(k-1)
    b(i) = errDist(ref(i))^2 - errDist(ref(k))^2 - xap(ref(i))^2
            - yap(ref(i))^2 + xap(ref(k))^2 + yap(ref(k))^2;
end

estPos = pinv(A)*b;
xs = estPos(1);
ys = estPos(2);

error = sqrt((xs - xt)^2 + (ys - yt)^2);


%This function returns the transmission coverage between a
        mobile station
%and an access point (CISCO Aironet 350) after a link budget
        procedure
%based on the Log-distance path loss model.

function d = maxDistance(Ptx,fb,f,gamma,sigma)

%Parameters:
%
%Ptx = Transmitted power [dBm]
%fb = Transmission rate [Mbps]
%f = signal frequency [Mhz]
%gamma = path loss exponent (frequency,environment)
%sigma = standard deviation of the gaussian-fading term [dB]

switch fb
    case 1
        Sdbm = -94;
    case 2
        Sdbm = -91;
    case 5.5
        Sdbm = -87;
    case 11
        Sdbm = -82;
    otherwise
        error('Only 1,2,5.5 or 11 Mbps are used in this case');
end

%fading term:
Xg = sigma*randn;

K = Ptx - Sdbm + 27.55 - 20*log10(f) - Xg;
K = K./(10*gamma);
```

```matlab
d = 10^K;

end


%This function returns the indoor Path Loss attenuation according to a
%modified COST231-Motley model [in dBm]

function Pl = pathLossModel(f,plExpIN,plExpOUT,d,din,sigma2x,Lwo,Lwi,loc)

%Parameters:
%
%f = signal frequency [Mhz]
%plExp = path loss exponent (frequency,environment)
%sigma2x = standard deviation of the gaussian-fading term [dB]
%Lwo = outside-wall loss
%Lwi = indoor-wall loss
%d = distance [m]
%din = is the distance until which the environment is considered "indoor"
%loc is a flag, it is set to 1 if we consider an indoor environment, 0 for
%outdoor one.

%fading,cable and body loss term:
Xg = sqrt(sigma2x)*randn;

if loc==0 %outdoor
    plExp = (din*plExpIN + (d-din)*plExpOUT)/d;
    Pl = -27.55 + 20*log10(f) + 10*plExp*log10(d) + Lwi + Xg + Lwo; %indoor + residual outdoor
elseif loc==1 %indoor
    Pl = -27.55 + 20*log10(f) + 10*plExpIN*log10(d) + Xg + Lwi;
end

end


%This function generates the coordinates of the mobile station and
%calculates the distances between a target node and the reference nodes.
function [xt,yt,distances] = rangingDist(xref,yref,areaside)
n = length(xref);
AP = [xref,yref];
flag = 1;

while(flag)
    xt = areaside*rand;
    yt = areaside*rand;

    msx = xt.*ones(n,1);
    msy = yt.*ones(n,1);
    MS = [msx,msy];
    distances = sqrt(sum((AP - MS).^2,2));

    if (isempty(find(distances==0,1)))
        flag = 0;
    end
end

end
```

```
% function rssiError = RSSImodel(alpha,APcoords,lendmarks,
      MScoords,pathLexp,sigma2,Nref)
%
% n=3:Nref;
%
% pathLexp = 10^(pathLexp/10);
%
% for i=1:length(n)
%     R(i)=2*sqrt(gammaincinv(alpha,n(i)*0.5));
%     for j=1:n(i)
%         t1(j) = (-pathLexp*(MScoords(1)-APcoords(lendmarks(i)
      ,1)))/...
%             ((MScoords(1)-APcoords(lendmarks(i),1))^2+(
      MScoords(2)-APcoords(lendmarks(i),2))^2);
%         t2(j) = (-pathLexp*(MScoords(2)-APcoords(lendmarks(i)
      ,2)))/...
%             ((MScoords(1)-APcoords(lendmarks(i),1))^2+(
      MScoords(2)-APcoords(lendmarks(i),2))^2);
%     end
%     a = sum(t1.^2./sigma2);
%     b = sum(t2.^2./sigma2);
%     c = sum((2*t1.*t2)./sigma2);
%     d = -R(i)^2;
%
%     rmax(i) = sqrt(-2*d/...
%         (a+b)+sqrt((a-b)^2+c^2));
%
%     rmin(i) = sqrt(-2*d/...
%         (a+b)-sqrt((a-b)^2+c^2));
%
%     rssiError(i) = sqrt(rmax(i)*rmin(i)*0.5);
% end

%This function calculates the localization estimation
      uncertainty-->mean error for a fixed number of reference
      nodes (n)
%INPUT:
%alpha = degree of confidence
%coord = set of reference nodes coordinates
%target = coordinates of the target device
%pathExp = path loss exponent of the log distance attenuation
      model
%sigma2 = variance of the gaussian error/variation of signal
      strength
%OUTPUT
%rssError = mean error

function rssiError = RSSImodel(alpha,coord,target,pathExp,sigma2
      )

n = size(coord,1);
Rn = 2*sqrt(gammaincinv(alpha,(0.5*n))); %hypersphere alpha-
      confidence radius
x = coord(:,1);
y = coord(:,2);
t = zeros(size(coord,1),size(coord,2));

for i=1:n
    t(i,1) = -pathExp*(target(1) - x(i))/...
        ((target(1) - x(i))^2 + (target(2) - y(i))^2);
    t(i,2) = -pathExp*(target(2) - y(i))/...
        ((target(1) - x(i))^2 + (target(2) - y(i))^2);
end
a = sum((t(:,1).^2)./sigma2);
b = sum((t(:,2).^2)./sigma2);
c = sum((2*t(:,1).*t(:,2))./sigma2);
```

```
d = -Rn^2;

rmax = sqrt((-2*d)/((a+b)+sqrt((a-b)^2+c^2)));

rmin = sqrt((-2*d)/((a+b)-sqrt((a-b)^2+c^2)));

%rssiError = sqrt(0.5*rmax*rmin);

k = -2*log(1-alpha);
c1 = rmax^2/k;
c2 = rmin^2/k;

rssiError = 0.75*sqrt(c1 + c2);

end


%This function generates a set of wireless Access Point
    uniformly
%distributed in a square area of side L, which must be greater
    than maximum
%transmission range of a mobile station. It generates also the
    position of
%a mobile station in this area, which represents the localizing
    node, and
%returns a matrix containing the position of the APs and the
%non-corrupted-by-noise ranges between APs and the MS.

function [APcoords,MScoords,distances] = setupNet(Ntot,L)

%Ntot = number of total APs in the area
%L = area side [m]

distances = zeros(1,Ntot);
APcoords = zeros(Ntot,2);

MScoords = L.*rand(1,2);

for i=1:Ntot
    APcoords(i,1) = rand*L;
    APcoords(i,2) = rand*L;

    distances(i) = sqrt((APcoords(i,1) - MScoords(1))^2 + (
        APcoords(i,2) - MScoords(2))^2);

    while (distances(i) == 0)
        APcoords(i,1) = rand*L;
        APcoords(i,2) = rand*L;
        distances(i) = sqrt((APcoords(i,1) - MScoords(1))^2 + (
            APcoords(i,2) - MScoords(2))^2);
    end
end

scatter(APcoords(:,1),APcoords(:,2),'r');
axis([0 L 0 L]);
xlabel('x [m]');
ylabel('y [m]');
box on;
% hold on
% scatter(MScoords(1),MScoords(2),'filled');
% hold off


end


%This function calculates the LS matrix A.
```

```
%INPUT:
%coords = matrix of the topology coordinates
%f = is a flag which chooses the method for the calculation of A
        (last node dependent vs independent one)
%OUTPUT:
%A = the LS matrix
%t[a,b,c] = the elements of A'*A (symmetric 2x2 matrix)
%lambda = is the minimum eigenvalue of A'*A

function lambda = topologyProjection(coord,f)

if (size(coord,2)~=2)
    error('We are considering only the 2-dimensional plane!')
end

n = size(coord,1);
x = coord(:,1);
y = coord(:,2);

switch f
    case 1 %Di Benedetto last node dependent mode [\ref{UWB}]
        for i=1:n-1
            A(i,1) = x(i) - x(n);
            A(i,2) = y(i) - y(n);
        end
        A = -2*A;
    case 2 %last node independent mode
        for i=1:n
            A(i,1) = x(i) - (1/n)*sum(x);
            A(i,2) = y(i) - (1/n)*sum(y);
        end
    otherwise
        error('f is only 1 or 2!')
end
T = A'*A;
a = T(1,1);
b = T(1,2); %= T(2,1)
c = T(2,2);
t= [a,b,c]';
lambda = min(eig(T));
%lambda = 0.5*((a+c) - sqrt((a+c)^2 - 4*(a*c-b^2)));

end


%This function calculates the upper bound of the positioning
       estimation
%error.
%INPUT:
%A = linear system (LS) matrix
%sigma2r = variance of the ranging error
%distRef = distances between the target and the reference nodes,
        is a
%vector of length k, where k is the number of reference nodes

function [bound,lambdaMin,phi,gamma] = upperBound(A,sigma2r,
       distRef)

%A is (k-1)x2 where k is the number of reference node, k =
       length(distRef)
k = length(distRef);
%calculation of the first term: phi
lambdaMin = min(eig(A'*A));
phi = 1/sqrt(lambdaMin);
%calculation of the second term: zeta
%deltaE:
```

```
varDe = 4*sigma2r*(distRef(1:end-1)).^2 + (distRef(end)*ones(k
        -1,1)).^2;
deltaE = sqrt(varDe).*randn(k-1,1);
%epsilon:
alfa = 16*(pi*sigma2r)^2;
z = (sqrt(sigma2r).*randn(k-1,1)).^2 - (sqrt(sigma2r).*randn(k
        -1,1)).^2;
arg = (2*pi/(alfa)).*abs(z);
epsilon = (2/(alfa)).*besselk(0,arg);
%
gamma = norm(deltaE) + norm(epsilon);
%bound
bound = phi*gamma;

end
\end{llisting}

%OUTPUT:
%coord = is a nx2 matrix containing the plan-coordinates of the
        nodes

function coord = crossTopology(n,s,areaside)

A = areaside;
xo = areaside/2;
yo = areaside/2;

Nx = ceil(n/2);
Ny = floor(n/2);

nxuptot = floor((A-xo)/s);
nxdtot = floor(xo/s);
nxtot = nxuptot + nxdtot;
nyuptot = floor((A-yo)/s);
nydtot = floor(yo/s);
nytot = nyuptot + nydtot;

%asse x
if (nxuptot < nxdtot)
    nxup = floor((nxuptot/nxtot)*Nx);
    nxdown = ceil((nxdtot/nxtot)*Nx);

else
    nxup = ceil((nxuptot/nxtot)*Nx);
    nxdown = floor((nxdtot/nxtot)*Nx);

end
x1 = xo - nxdown*s;
x2 = xo + nxup*s;
xh = x1:s:x2;
xh = xh(1:end-1);
yh = yo*ones(1,Nx);

%asse y
if (nyuptot < nydtot)
    nyup = floor((nyuptot/nytot)*Ny);
    nydown = ceil((nydtot/nytot)*Ny);
else
    nyup = ceil((nyuptot/nytot)*Ny);
    nydown = floor((nydtot/nytot)*Ny);
end
y1 = yo - nydown*s;
y2 = yo + nyup*s;
yv = y1:s:y2;
yv = yv(1:end-1);
yshift = yv(floor(length(yv)/2)+1:end) + s;
yv(floor(length(yv)/2)+1:end) = yshift;
```

```
xv = x0*ones(1,Ny);

x = [xh xv];
y = [yh yv];

coord = [x',y'];

scatter(x,y)

%This functions generates a regular-polygonal topology with a
        fixed
%side of the polygonum, that means the distance between Access
        Points is
%fixed.
%INPUTS:
%n = vertices of the polygon, that is the number of nodes
%s = is the side of the polygonum
%areaside = is the area considered
%OUTPUT:
%coord = is a nx2 matrix containing the plan-coordinates of the
        nodes

function coord = fixedDistPolyTopology(n,s,areaside)

if n == 3
    k = 2;
elseif n == 4
    k = 4;
else
    k= inf;
end

theta = linspace(0,2*pi,n+1);
theta = theta(1:end-1);

%from the side we can calculate the circumradius

r = sqrt(s^2 * (cot(pi/n)/sin(2*pi/n)));
C = areaside/2;

%center coordinates
xc = C;
yc = C;

%vertexes coordinates:

x = xc + r*cos(theta + pi/k);
y = yc + r*sin(theta + pi/k);

coord = [x',y'];

%scatter(x,y)

end


%Nested topology (squares, triangles and single point)

function coord = nestedTopology(n,areaside,s)

%q = number of squares
%t = number of triangles
%p = number of central points

xap = zeros(1,n);
yap = zeros(1,n);
```

```
k = floor(n/4);
r = n - k*4;

if(k==0 || r==2)
    q = k - 2;
    if (q<0)
        q = 0;
    end
    t = floor((n - q*4)/3);
    p = floor(n - q*4 - t*3);
else
    q = floor(n/4);
    t = floor((n - q*4)/3);
    p = floor(n - q*4 - t*3);
end

if p == 1
    xap(1) = areaside/2;
    yap(1) = areaside/2;
else
    p = 0;
end

f = 1;
end1 = 0;
if t~=0
    end1 = 3*t+p;
    for i=(1+p):3:(end1+p)
        coordt = fixedDistPolyTopology(3,f*s,areaside);
        xap(i:i+2) = coordt(:,1);
        yap(i:i+2)= coordt(:,2);
        f = f+1;
    end
end

if q~=0
    end2 = end1 + 4*q + p;
    for i=end1+1+p:4:end2
        coordq = fixedDistPolyTopology(4,f*s,areaside);
        xap(i:i+3) = coordq(:,1);
        yap(i:i+3) = coordq(:,2);
        f = f+1;
    end
end

coord = [xap' , yap'];

scatter(xap,yap)


%This functions generates a regular-polygonal topology inside a
        fixed area
%INPUTS:
%n = vertices of the polygon, that is the number of nodes
%areaside = is the area considered, equal to twice the radius of
        the
%circumference inscribing the polygon
%OUTPUT:
%coord = is a nx2 matrix containing the plan-coordinates of the
        nodes

function coord = polyTopology(n,areaside)

theta = linspace(0,2*pi,n+1);
theta = theta(1:end-1);
```

```
R = areaside/2;

%center coordinates:
xc = R;
yc = R;

%vertex coordinates:
x = xc + R*cos(theta);
y = yc + R*sin(theta);

coord = [x',y'];

%scatter(x,y)

end


%This functions generates a QAM-based topology
%INPUTS:
%n = the number of nodes
%areaside = is the area considered
%OUTPUT:
%coord = is a nx2 matrix containing the plan−coordinates of the nodes

function coord = qamBasedTopology(n,areaside)

M = 2^nextpow2(n);
h = modem.qammod(M);
a = h.constellation;
b = real(a);
c = imag(a);
K = 0.5*areaside/max(length(unique(b))−1,length(unique(c))−1);
b = 0.5*areaside + K.*b;
c = 0.5*areaside + K.*c;

over1 = floor((M-n)/2);
over2 = ceil((M-n)/2);
xap = b(over1+1:(M-over2));
yap = c(over1+1:(M-over2));
coord = [xap',yap'];
scatter(xap,yap)
axis([0 areaside 0 areaside]);


%This functions generates a random topology
%INPUTS:
%n = the number of nodes
%areaside = is the area considered
%OUTPUT:
%coord = is a nx2 matrix containing the plan−coordinates of the nodes

function coord = randomTopology(n,areaside)

xap = areaside.*rand(n,1);
yap = areaside.*rand(n,1);

coord = [xap,yap];
```

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