TV White Space and LTE Network Optimization towards Energy Efficiency in Suburban and Rural Scenarios

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Abstract— **The radio spectrum is a limited resource. Demand for wireless communication services is increasing exponentially, stressing the availability of radio spectrum to accommodate new services. TV White Space (TVWS) technologies allow a dynamic usage of the spectrum. These technologies provide wireless connectivity, in the channels of the Very High Frequency (VHF) and Ultra High Frequency (UHF) television broadcasting bands. In this paper, we investigate and compare the coverage range, network capacity, and network energy efficiency for TVWS technologies and LTE. We consider Ghent, Belgium and Boyeros, Havana, Cuba to evaluate a realistic outdoor suburban and rural area, respectively. The comparison shows that TVWS networks have an energy efficiency 9-12 times higher than LTE networks.**

Index Terms—**Wireless Networks, Network Planning, Coverage Prediction, TVWS, Energy Efficiency**

I. INTRODUCTION

WIRELESS communication services are mainly provided under a fixed spectrum allocation. This spectrum allocation process is highly inefficient, leading to significant spectrum underutilization [1]. A radio spectrum usage survey in Virginia, United States, from 30 MHz to 3 GHz, revealed that less than 20% is in use at any location and at any given time [1]. A survey in Brno, Czech Republic and Paris, France indicated even a lower spectrum usage in the range from 400 MHz to 3 GHz [2]. A study to account the percentage of TV White Spaces (TVWS) in 11 European countries revealed that 56% of UHF spectrum is not in use at any location and at any given time [3]. The estimated percentage of unused UHF spectrum in Belgium is 69% [3]. Although assigned by the local regulatory domain, only 44% of VHF and UHF spectrum is in use in Havana City and it will decrease to 12% after analog broadcasting switch-off [4].

TVWS technologies dynamically allocate the required spectrum. The spectrum allocation is performed by means of cognitive radios with local spectrum sensing techniques and/or a geo-location database [5], [6]. Two main TVWS standards have been established based on the new dynamic spectrum-sharing paradigm: IEEE 802.22 (latest update IEEE 802.22b) and IEEE 802.11af [7], [8], [9]. IEEE 802.22 was the first complete cognitive radio standard, including spectrum sensing techniques and geo-location capability with the provision to access a database that stores, by geographic location, the permissible frequencies and operating parameters [10]. An amendment in IEEE 802.11af enables geolocation database access to TVWS. The location algorithm allows the implementation of a closed-loop database. This database provides to Base Stations (BS) the white spaces availability, but also receives feedback from the geo-location of all network devices, their frequencies and emission footprints. By accessing and using this information, it is possible to coordinate and to make intelligent decisions about the most effective way to utilize the available spectrum [9], [11].

IEEE 802.11p-2010 added more flexible mobile capability in Vehicular Ad-Hoc Networks (VANETs). This standard has been superseded by IEEE 802.11-2012 in which the content is now incorporated. In [12] the performance of VANET communications coexisting with DVB-T2 has been studied.

Several trials have been conducted worldwide to evaluate TVWS technologies [13]. In a trial with IEEE 802.22, a Bit Error Rate (BER) of 10^{-6} was reported at a distance of 6.3 km (one site measurement), for 3/4 64-QAM with an Equivalent Isotropic Radiated Power (EIRP) of 34.6 dBm, BS antenna height 20 m, receiver antenna height of 12 m and receiver antenna gain of 7.65 dBi [14]. A field trial for Line-Of-Sight (LOS) studied the bitrate versus coverage of a TVWS prototype in four outdoor measurement sites, considering different link margin and modulation schemes [15].

In [16], the authors analyzed the coverage for 802.11af BSs in a generic scenario, for different interference conditions and BS antenna heights. A bitrate performance comparison of TVWS technology and WiFi is presented in [17], considering the effect of interference and medium access congestion for Carrier Sense Multiple Access with Collision Avoidance

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(CSMA/CA) mode in IEEE 802.11af. Also [18] presented a throughput study of IEEE 802.11af for a rural area, considering the population density as reference. Several studies have investigated the white space channel availability for different interference considerations, protection margins and occupancy thresholds [3], [19], [20].

The power consumption models and energy efficiency for Long-Term Evolution (LTE) networks have been widely studied (i.e. [21], [22], [23], [24], [25]). For TVWS these parameters have not been properly investigated. A power consumption measurement for two different TVWS hardware is reported in [26], but neither power consumption model, energy efficiency nor network optimization is investigated.

In this paper we compare the coverage, performance and energy efficiency of TVWS technologies and LTE, in a suburban and a rural scenario, for the first time according to the authors' knowledge. A network optimization towards reduced power consumption is performed. We consider realistic user and traffic densities provided by local network operators. A novel power consumption model for TVWS technologies is proposed.

The outline of this paper is as follows. In Section II we describe the suburban and rural scenarios, the technology link budgets, the power consumption models, the energy efficiency metric, and the optimization algorithm. In Section III, we present the network simulation results for the proposed scenarios. Conclusions are presented in Section IV.

II. METHOD

First, we define the characteristics of each scenario and the link budget for each technology. The maximum coverage range and minimum required number of BS are estimated. Finally, an optimized network design towards minimum power consumption for TVWS and LTE is performed.

A. Evaluation Scenarios

We consider Ghent City, Belgium and Boyeros municipality outskirts in Havana, Cuba for the evaluation of a realistic suburban and rural area, respectively. Fig. 1a shows the target area (68 km^2) that needs to be covered in Ghent City. Fig. 1b shows the target area (169 km^2) that needs to be covered in Boyeros municipality. This area also includes some small towns at the outskirts of Havana City with dispersed population.

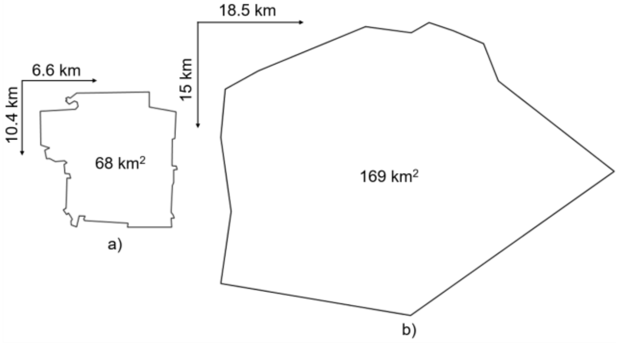

Fig. 1. The area to be covered, a) Ghent City (Suburban), b) Boyeros municipality – Havana outskirts (Rural).

We consider a wireless network setup based on a fixed outdoor over-roof antenna configuration. The end-point connection at the user's home is provided by a transceiver to an Ethernet or WiFi network. Fig. 2 shows the initial considered configuration.

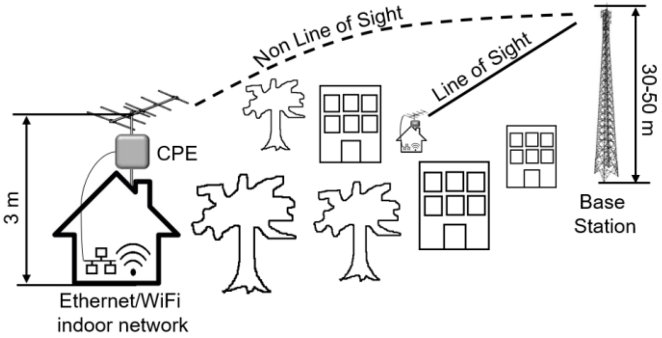

Fig. 2. Configuration for evaluation of TVWS and LTE technologies.

The wireless network design is based on a requirement of 90% of the locations covered at the edge of the coverage area during 99% of the time. The network must be able to handle up to 224 simultaneous connections in the suburban area and 135 simultaneous connections in the rural area. Some users require 64 kbps (voice users, approximately 9% of total users) and others 1 Mbps (data users, approximately 91% of total users) [27]. The network planning is usually done for the peak traffic periods. Both user and traffic densities are based on real statistical data provided by the local operators for the peak network traffic to consider the worst case scenario.

The users are distributed uniformly and pseudo-randomly over the whole area. As consequence, each pixel in the map has the same probability to receive a user, with 0.09 probability of voice users and 0.91 of data users. The bitrate distribution is a probability mass function where the bitrate assignment can be considered as a discrete random variable defined by the sample space (discrete set of all possible outcomes, i.e. 64 kbps or 1 Mbps).

In both suburban and rural scenarios, the antenna configuration is Single-Input Single-Output (SISO) with an omnidirectional radiation pattern. Therefore, the BS coverage area is represented by a circle with center in the BS location coordinates. LTE, IEEE 802.22b and IEEE 802.11af provide support for Multi-Input Multi-Output (MIMO) up to 4x4, although it is not widely industrialized yet [28], [8], [9]. The highest Modulation and Coding Schemes (MCS) for IEEE 802.22b (256-QAM schemes) are not implemented on commercial available hardware either. The influence of a MIMO 4x4 configuration will be evaluated for both scenarios (considering future hardware availability).

B. Link Budgets and Propagation Models

To estimate the range of each BS, the maximum allowable path loss PL_{max} [dB] for an acceptable BER performance has to be determined [21], [29]. To this aim, a link budget is defined according to the technology specifications and the scenario characteristics [29]. Table I lists the link budget parameters for each technology, in both scenarios.

TABLE I
LINK BUDGET PARAMETERS (SUBURBAN/RURAL AREA)

Parameter	802.22	802.22b	802.11af	LTE	Unit
Radiated Power	36	36	36	36	dBm
Frequency	602/605	602/605	602/605	821	MHz
Bandwidth	8/6	8/6	8/6	10/5	MHz
Total Subcarriers	2048	1024	144	1024/512	-
Used Subcarriers	1680	832	114	601/301	-
Frequency Sampling Factor	1.142	0.9325	1.142	1.536	-
BS Antenna Height	50/30	50/30	50/30	50/30	m
Cell Interference Margin	0	0	0	2	dB
MIMO Gain	-	12	12	12	dB
Receiver Antenna Height	3	3	3	3	m
Receiver Antenna Gain	11.5	11.5	11.5	11.5	dB
Receiver Feeder Losses	0.04	0.04	0.04	0.04	dB
Noise Figure	4	4	4	7	dB
Shadow Margin	7.91/5.5	7.91/5.5	7.91/5.5	7.91/5.5	dB
Fade Margin	7.37/4	7.37/4	7.37/4	7.37/4	dB
Receiver Signal to Noise Ratio (SNR)	4.3 10.2 12.4 18.3 19.7	4.3 10.2 12.4 18.3 19.7 26.9 28.2	3.8 8.0 15.1 25.2 30.4	3.0 10.5 14.0 22.0 29.4	dB
Bitrate	@ 8 MHz		@ 10 MHz		Mbps
	6.0 12.0 16.1 24.1 27.2	6.0 12.0 16.1 24.1 27.2 32.2 42.3	2.4 7.2 14.4 24.0 32.0	4.32 6.3 16.8 25.2 38.7	
	@ 6 MHz		@ 5 MHz		
	4.5 9.0 12.1 18.1 20.4	4.5 9.0 12.1 18.1 20.4 24.2 31.7	1.8 5.4 10.8 18.0 24.0	4.2 5.7 8.5 11.3 16.9	

Main link budget differences from one scenario to another one arise in the parameters related to the propagation environment (i.e. shadowing and fading margin) and the regulatory domain (i.e. bandwidth, frequency). The radiated power (EIRP) corresponds to the maximum allowable [8]. The bandwidth corresponds to the channel distribution in each region [30], [31].

The OFDM parameters are retrieved from the standards [7], [8], [9], [32]. Note that the frequency sampling factor is the ratio of the sampling frequency and the channel bandwidth. The SNR is recommended for IEEE 802.22 and IEEE 802.22b [7], [8] and guarantees a Bit Error Rate better than 10^{-7}, considering the co-channel interference of a DVB-T2 TV broadcasting network [33]. For LTE and IEEE 802.11af, we consider the SNR reported in private interviews with manufacturers. Other parameters such as antenna heights, antenna gains and feeder losses are also typical implementation values, as reported by manufacturers.

The cell interference margin for TVWS technologies is 0 dB. We consider TVWS operation in non-interfering channels only (25 non-interfering TVWS channels available in Ghent [34]) and the strictest spectrum-sensing modes defined in the standards. The channel allocation is based on the detection of the wireless beacon (IEEE 802.22.1). It means that a channel will be considered occupied if a wireless beacon frame, with a level equal or higher than -116 dBm is detected. For a complementary protection from/to the primary TV broadcasting services, we assume a geo-location database with a similar constraint.

Even under the considered constraints, the coexistence of joint IEEE 802.22 and IEEE 802.11af operating in the same region is not solved yet. In such condition, the probability of IEEE 802.22 users to get access to the spectrum resources is higher [35]. For a fair comparison, we assume that a single TVWS technology is deployed in the target area at the same time. State-of-the-art TVWS receivers have a noise figure from 3 to 4 dB [36]. To evaluate the worst case scenario, all calculations are based on a noise figure of 4 dB. For LTE, the macrocell propagation model proposed by ETSI (European Telecommunications Standards Institute) considers a Customer-Premises Equipment (CPE) noise figure of 9 dB [37]. The noise figure of current fixed outdoor LTE receivers (in the frequency of interest) varies from 4 dB to 8 dB. We assume a noise figure of 7 dB for LTE fixed outdoor CPE (see Table I).

In suburban Ghent, we consider a shadow margin of 7.91 dB, for 90% of locations covered at a certain distance from the transmitter [38] and a fading margin of 7.37 dB for 99% availability [39]. Boyeros municipality in Havana outskirts, is a rural area with a low foliage density. To achieve the same coverage and availability percentages, we consider a shadow margin of 5.5 dB and a fading margin of 4 dB [39]. Note that over-roof reception network planning does not require accounting for building penetration losses [40].

Different path loss models have been studied to estimate the path loss in the UHF band. For instance, the ITU-R P.1546 presents a method for point-to-area radio propagation predictions for terrestrial services and was originally derived from measurements performed for VHF and UHF broadcasting [41], ITU-R P.1812 for path-specific propagation prediction method for point-to-area terrestrial services at VHF and UHF bands [42] and Okumura-Hata model [43]. For Ghent City an experimental path loss model based on extensive measurement campaign is described in [38]. For Boyeros (rural scenario) an experimental path loss model is not available.

Fig. 3 shows a comparison among Okumura-Hata, ITU-R P.1546 and Ghent Model. Note that ITU-R P.1812 requires a digital terrain database or 3D environmental map, which is not available for the rural scenario [42].

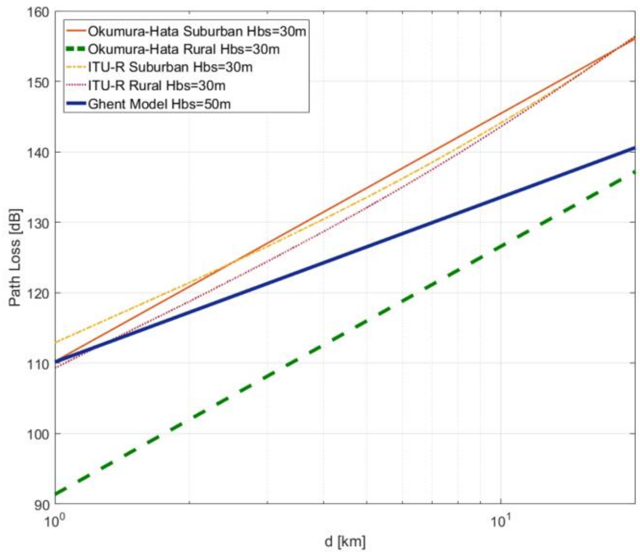

Fig. 3. Path loss models.

The ITU-R P.1546 model and Okumura-Hata model for suburban scenarios retrieve similar results. Nevertheless, for a rural scenario there is a higher difference between both models. Considering the same conditions of the Ghent model measurement campaign [38], the ITU-R P.1546 even with the rural correction factors overestimates the path loss for Ghent City. The rural consideration of Okumura-Hata model is a quasi-open area at the receiver location, which better fits with the topology at Havana outskirts. Therefore, for the rural scenario the coverage prediction is based on Okumura-Hata path loss model.

C. Minimum required number of Base Stations

The minimum required number of BS depends on both the area to be covered and the served traffic. To cover a target area A_T (km^2), the minimum required number of BS (N_{BSa}) can be defined as a function of the maximal BS coverage range R (km), with $\lceil \cdot \rceil$ the ceil function:

$$N_{BSa} = \left\lceil \frac{A_T}{\pi \cdot R^2} \right\rceil \tag{1}$$

Taking into consideration the total traffic requirement T (Mbps) within the area A_T (i.e. the sum of the individual traffic requirements of all simultaneous users), the minimum required number of BS (N_{BSt}) as a function of the bitrate served by a single BS, B_{BS} (Mbps), can be defined by the following equation:

$$N_{BSt} = \left\lceil \frac{T}{B_{BS}} \right\rceil \tag{2}$$

The actually required number of BS (N_{BS_total}) depends also on the target area topology, the distribution of possible BS locations and the network optimization algorithm. Equation 3 provides a minimum to the required number of BS.

$$N_{BS\_total} \geq \max\left(N_{BSa}, N_{BSt}\right) \tag{3}$$

D. Energy Efficiency Metric

A metric to account for the energy efficiency of a single BS is defined in [22]. An extension of this metric, to account for the energy efficiency of the whole network configuration is defined in [44]. The average network energy efficiency EE_n (km^2·Mbps/W) for t different user distributions and a certain coverage percentage of users c_i can be defined as follows:

$$EE_n = \frac{1}{t} \cdot \sum_{i=1}^{t} \frac{c_i \cdot A_T \cdot U \cdot \sum_{j=1}^{m} B_{ij}}{\sum_{j=1}^{m} P_{BS_{ij}}} \tag{4}$$

where A_T is target area, U is the number of users in the target area, B_{ij} represents the total bitrate provided by BS j to the users population i, m is the total number of BS and P_{BSij} represents the power consumption of the BS_{ij}.

The power consumption of LTE BS has been studied in [22], [25], [24]. To account for the power consumption of each LTE BS we consider the model proposed in [22]. This model takes into account the radiated power, the amplifier efficiency and the radiation system efficiency. Fig. 4a shows the power consuming components of an LTE BS. We assume an optical backhaul power consumption of 32 W for LTE [45].

In Fig. 4b we propose a power consumption model for the TVWS BS. This model comprises three power-consuming components: the Radio Unit (RU), the Power Supply (Power over Ethernet (PoE)) and the Optical Backhaul.

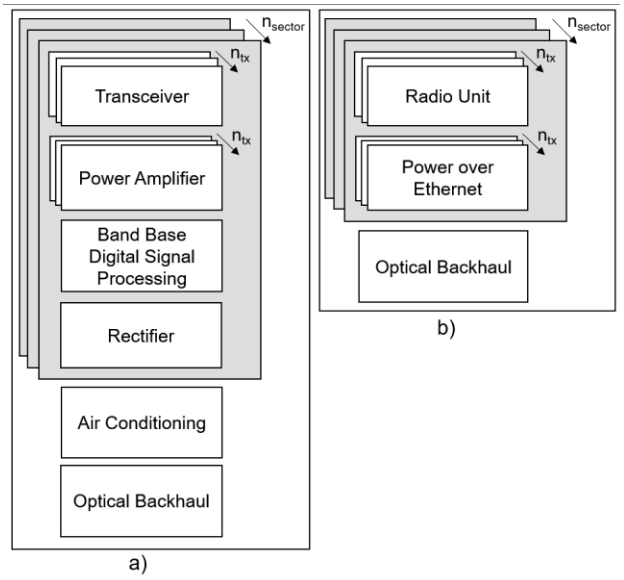

Fig. 4. Block diagram of power-consuming components a) LTE [22] b) TVWS.

The total power consumption of a TVWS BS can be calculated as follows:

$$P_{BS} = P_{bh} + P_{idle} + n_{st} \cdot n_{tx} \cdot \alpha \cdot \left(\frac{P_r}{\eta_{ru}} + P_{PoE} \right) \qquad (5)$$

We consider the power consumption of the optical backhaul P_{bh} to be constant and independent from the number of sectors and transmitters. The PoE power consumption (P_{PoE}) and RU power consumption varies with the traffic load factor α. We will consider $\alpha = 1$ to investigate the maximal power consumption of the BS (worst-case scenario). For OFDM applications, the power amplifier of the RU should operate in the linear region. The relation between the transmitter output power and BS power consumption is nearly linear [25]. The power consumption of the RU can be correlated with the radiated power P_r (for n_{st} sectors and n_{tx} transmitters) by means of a linear function. The slope (η_{ru}) of this function is the ratio of radiated per consumed power. For the maximum power of 1W in the amplifier output (equivalent to a maximum radiated power $P_{r\max} = 4$W) the RU maximum power consumption ($P_{BS\max}$) is approximately 28W [26]. However, not all the consumed power can be correlated with the radiated power. The RU also has an idle power consumption P_{idle} = 6W for P_r = 0 W [36]. Thus, η_{ru} can be calculated as follows:

$$\eta_{ru} = \frac{P_{r\max}}{P_{BS\max} - P_{idle}} = 0.182 \qquad (6)$$

Table II lists the power consumption values for a TVWS BS.

TABLE II
TVWS POWER MODEL PARAMETERS

Parameter	Value	Unit
P_{bh} [45]	32	W
P_{PoE} [46]	4	W
P_{idle} [36]	6	W
η_{ru}	0.182	-

For a single transmitter and sector with P_r = 4 W and α = 1 the power consumption of a TVWS BS is as low as 64 W. Digital Signal Processing (DSP) on TVWS BSs is generally implemented by a dedicated chipset (i.e. [36]). This is highly energy efficient [47] but, as a drawback, BSs are not upgradeable to support future standards or re-scale.

E. Optimization algorithm

The network planning is performed by GRAND (Green Radio and Access Network Design) optimization algorithm described in [27]. First, the network traffic is generated for 40 simulations (40 different spatial user distributions and user bitrate distributions). Fig. 5 shows a heuristic algorithm towards minimizing the network power consumption. The algorithm seeks to connect each user to the BS with the lowest path loss and lower BS powers in order to reduce the power consumption by reducing the radiated power. The heuristic will not be the absolute best solution, but a solution that solves the optimization problem in a reasonable time frame.

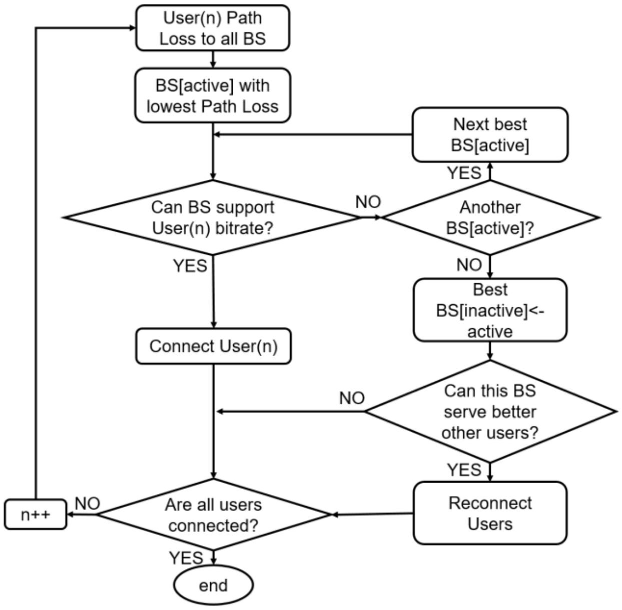

Fig. 5. Network optimization algorithm [27].

For each simulation, the software calculates the path loss between a user and all possible BSs. The algorithm first seeks to connect each user to the BS corresponding with the lowest path loss. A certain user is connected to a BS only if the BS is already active and still can support the bitrate demanded by the user. In this way, the algorithm tends to minimize the number of active BS. In case a BS can not support the current user the algorithm seeks for the next already active BS with lowest path loss. In case no active BS can be found, the algorithm will activate the most appropriate BS (lowest path loss) from the inactive ones. When a new BS is activated, the algorithm checks if users already connected can be switched in order to balance the network load. A certain user is only switched to another BS if the pass loss to the new BS is lower. The described algorithm is repeated until all users are evaluated. More details on the algorithm can be found in [27].

The progressive average for all simulations is calculated to validate a proper estimation of the percentage of users covered.

III. RESULTS

This section presents the results of the network simulations and optimizations for the considered scenarios.

A. Maximum coverage for one Base Station

Fig. 6 shows the BS bitrate versus coverage range for the suburban and rural area. For the maximum EIRP, IEEE 802.22b BS has a higher coverage range than LTE, IEEE 802.22 and IEEE 802.11af. The maximum coverage range for IEEE 802.22b is equal to 7.0 km in the suburban scenario and 17.6 km in the rural scenario (MCS 1/2 QPSK). The LTE BS has the lowest coverage range: 3.2 km and 12.1 km (1/2 QPSK), in the suburban and rural area, respectively. The lower coverage is due to a 3 dB higher noise factor compared with TVWS technologies and 2 to 4 dB higher required SNR than IEEE 802.22b. The latest version IEEE 802.22b achieves a 5 to 8% higher coverage range than IEEE 802.22 due to an improvement in the ratio of OFDM used from total subcarriers and a better sampling frequency factor. In comparison, IEEE 802.11af achieves a 15 to 30% lower coverage because it requires a higher SNR (an average 6 dB higher).

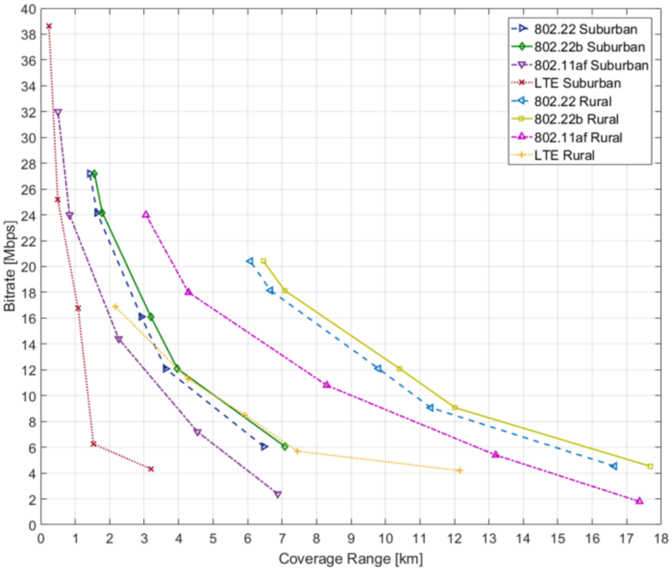

Fig. 6. BS comparison of bitrate versus coverage for the maximum EIRP.

B. *Network planning and optimization*

First, we simulate the network for the minimum required number of BS (see Equation 3). Fig. 7 and Fig. 8 show the minimum required number of BS in the suburban and rural scenario, respectively. These graphs represent the trade-off between coverage and capacity. For a higher bitrate (i.e. higher required SNR), the number of BS to satisfy a certain traffic (N_{BSt}) decreases. A higher SNR has as consequence, a reduction in coverage and the number of BS to cover a certain area (N_{BSa}) increases. IEEE 802.22 and IEEE 802.22b have the lowest required number of BS. This is because it has a better coverage per provided bitrate unit in both scenarios (see Fig. 6).

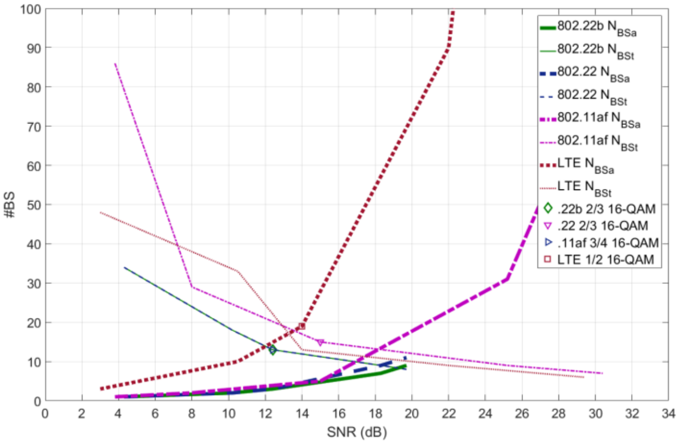

Fig. 7. Minimum required number of BS vs required SNR in the suburban scenario. The markers indicates the optimal MCSs.

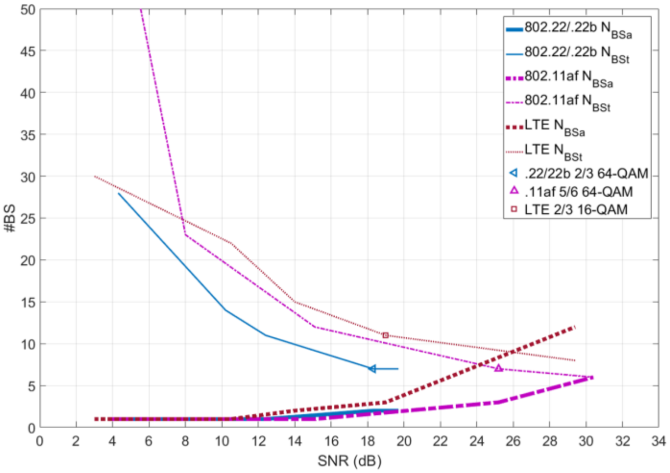

Fig. 8. Minimum required number of BS vs required SNR in the rural scenario. The markers indicates the optimal MCSs.

The minimum required number of BS locations in the rural area is lower for all the standards, due to a better propagation environment and lower traffic density.

In the suburban scenario, the lowest required number of BSs and highest percentage of users covered are achieved for the MCS 2/3 16-QAM for IEEE 802.22 and IEEE 802.22b, 3/4 16-QAM for IEEE 802.11af and 1/2 16-QAM for LTE (see markers in Fig. 7). Note that in the suburban scenario the MCS 2/3 16-QAM (IEEE 802.22 and IEEE 802.22b) does not has the lowest max (N_{BSa},N_{BSt}). Nevertheless, the best network planning in terms of energy efficiency is achieved when the network is designed to guarantee that all users can be connected with this MCS. This is because of for MCS with a similar minimum number of required BS, the area constraint (N_{BSa}) prevails due to the deviation caused by the area geometry and BS location distribution. In the rural scenario, the best trade-off is achieved for the MCS 2/3 64-QAM for IEEE 802.22 and IEEE 802.22b, 5/6 64-QAM for IEEE 802.11af and 2/3 16-QAM for LTE (see markers in Fig. 8).

Equation 3 provides a theoretical minimum N_{BS_total} been required a higher number of BS. This is due to the area geometry and BS location influence. Therefore, the number of BS is increased until we reach a mean coverage higher than 95%.

Fig. 9 shows the network coverage map for each technology in both scenarios for the most efficient MCSs in terms of energy efficiency. The optimal MCS yields the highest energy efficiency with the lowest number of BSs that allow to meeting both, the coverage and traffic demand. In the suburban scenario, the number of considered BS locations is 20 for IEEE 802.22 and 802.22b, 21 for IEEE 802.11af and 36 for LTE. In the rural scenario, the number of considered BS locations is 10 for all TVWS technologies and 13 for LTE. Although the target area in the rural scenario is more than two times larger than the suburban scenario, the number of BS locations can be reduced around to half (keeping a similar percentage of coverage). This is because the rural environment has a lower path loss and lower traffic requirement.

The mean percentage of users covered is 95% for LTE and higher than 96% for TVWS technologies in the suburban scenario. In the rural scenario the mean percentage of users covered is higher than 96% for IEEE 802.11af and LTE, and higher than 99% for IEEE 802.22 and IEEE 802.22b. The deviation of the mean value of the percentage of users covered is lower than 0.5% over the considered simulations.

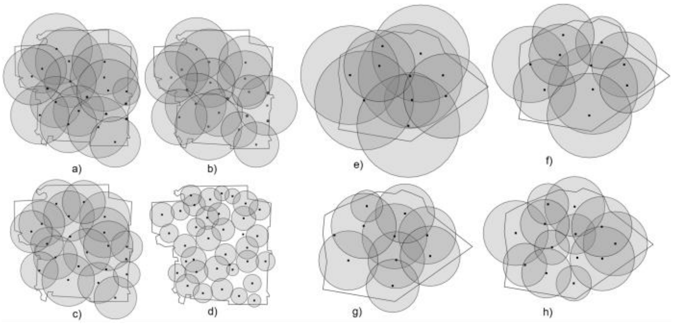

Fig. 9. Optimized networks (towards minimum power consumption) in Ghent area (suburban), for a) IEEE 802.22b, b) IEEE 802.22, c) IEEE 802.11af, d) LTE technology and Boyeros area (rural) for e) IEEE 802.22b, f) IEEE 802.22, g) IEEE 802.11af, h) LTE technology.

Fig. 10 shows the average network energy efficiency and its standard deviation for each technology. The best solution to cover the suburban area is IEEE 802.22b with an average network energy efficiency of 2996.8 km^2·Mbps/W. Note that the energy efficiency difference between IEEE 802.22b and IEEE 802.22 is lower than the standard deviation.

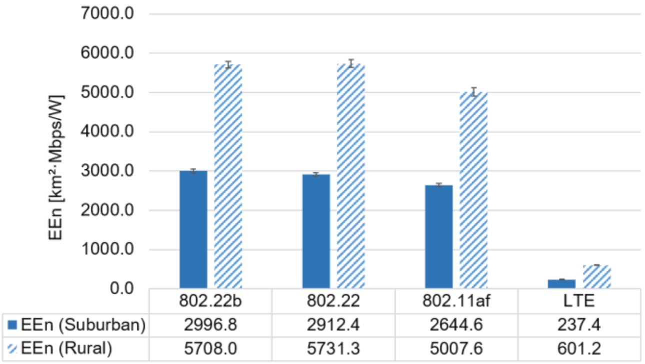

Fig. 10. Average network energy efficiency in the suburban and rural scenarios.

The LTE network has an energy efficiency more than 12 times lower. This is due to a lower coverage per provided bitrate unit (see Fig. 6) but also a higher network power consumption. The total power consumption for TVWS networks ranges from 1010 W (IEEE 802.22b) to 1044 W (IEEE 802.11af). The full LTE network has an average power consumption of 11883 W.

The energy efficiency in the rural scenario is higher than the energy efficiency in the suburban scenario due to a better propagation environment and lower traffic density. This leads towards a lower number of BSs and lower network power consumption. The network power consumption for the TVWS networks ranges from 489 W (IEEE 802.22) to 521 W (IEEE 802.11af) and 4362 W for LTE.

The best solutions to cover the rural area are IEEE 802.22b and IEEE 802.22 (difference lower than the standard deviation). This is because the slightly difference in coverage per bitrate provided (see Fig. 6) is not enough to compensate the deviation caused by the BS location distribution and area geometry.

C. *Influence of MIMO*

The diversity gain increases the coverage of each BS. As a consequence, the number of BSs can be reduced. In the suburban scenario with a MIMO 4x4 configuration the number of BSs can be reduced to 11 for TVWS technologies and 15 for LTE. The best trade-off between area covered and capacity is achieved for 3/4 64-QAM for IEEE 802.22b, 5/6 64-QAM for IEEE 802.11af and 1/2 16-QAM for LTE. In the rural scenario, the number of required BSs can be reduced to 5 for IEEE 802.22b, 8 for IEEE 802.11af and 10 for LTE.

Fig. 11 shows the average network energy efficiency for MIMO 4x4 compared with SISO configuration. In the suburban scenario, the energy efficiency of IEEE 802.22b with a 4x4 MIMO configuration is slightly increased by 4% while for LTE by 47% (compared with SISO).

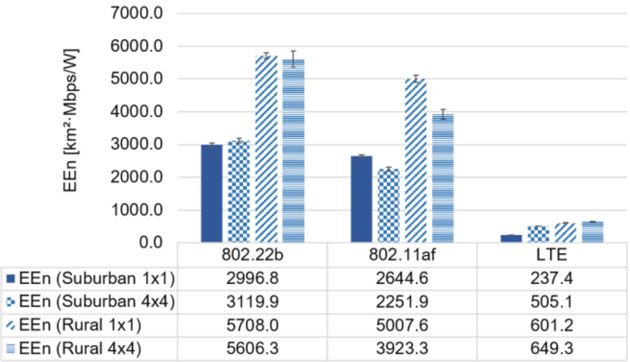

Fig. 11. Average network energy efficiency in the suburban and rural scenario. MIMO 4x4 versus SISO configuration.

For IEEE 802.11af the energy efficiency decreases approximately 15% when comparing with SISO. In the suburban scenario, four transmitting antennas significantly increases the network energy efficiency for LTE but not for TVWS. For LTE BSs, the transmitters consume less than 10% of the BS total consumed power. The coverage increase realized by the MIMO diversity gain, together with the reduction of BS sites, overcompensates the increase in the transmitters' power consumption. For TVWS BS the power consumption of the transmitters represents around 40% of the total consumed power. The increase in the power consumption of the transmitters is not always compensated.

For the rural scenario, the minimum required number of BS is always defined by the traffic constraint. Only 1 to 3 BS are required to cover the whole area however these can not support the traffic demand. The usage of four transmitters leads towards a higher power consumption not compensated by the coverage increase. As consequence, for the rural scenario the energy efficiency slightly increases by 7% for LTE, remaining approximately the same for IEEE 802.22b (the difference is less than the standard deviation), while decreases more than 21% for IEEE 802.11af. Nevertheless, all the technologies have a better performance in the rural scenario, prevailing the better propagation conditions.

IV. CONCLUSION

By using novel network planning software, we investigated the coverage, capacity and energy efficiency of TVWS networks, optimized towards reducing its power consumption, in realistic suburban and rural scenarios. For this aim, we proposed a model to determine the power consumption of TVWS networks. We also optimized and investigated an LTE network for a reference comparison. This comparison reveals that LTE has a lower energy efficiency in both suburban (approximately 12 times lower) and rural (approximately 9 times lower) scenario. IEEE 802.22b achieves the highest energy efficiency (12% higher than IEEE 802.11af).

For TVWS technologies, the use of a MIMO 4x4 configuration allows reducing the number of BS locations but does not significantly increase the energy efficiency in the considered scenarios.

Future research will consist of planning energy efficient Internet of Things (IoT) wireless networks in TVWS band. A huge density of devices will have to be considered and coverage, capacity and density will play a key role.

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