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DYNAMIC CHANNEL ALLOCATION FOR EFFICIENT WiFi OPERATION IN TV WHITE SPACES AND DVB-T SERVICE PROTECTION

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A b s t r a c t: The emergence of cognitive radio technologies for the spectral re-usage of the underutilized TV bands, i.e. TV White Spaces (TVWSs), leads to interference concerns for the Digital Video Broadcasting–Terrestrial (DVB-T) services. The DVB-T receivers have to be protected from aggregate interference from in-band cognitive technologies transmissions. The regulators have assessed and defined the protection criteria for this case. This paper proposes an iterative on-the-fly channel allocation algorithm for IEEE 802.11af operation in TVWSs, which allocates the WiFi channels based on the max distance approach, including DVB-T protection criteria from the European and USA regulatory bodies, i.e. the Electronic Communications Committee (ECC) and the Federal Communication Commission (FCC), respectively. The simulation analysis of the algorithm include realistic data for DVB-T modeling and Poisson point process for WiFi Access Points (APs) modeling. The results prove the performance increase introduced by the algorithm in terms of spatial capacity/coverage and DVB-T service protection.

Key words: DVB-T service protection; IEEE 802.11af channel allocation; aggregate in-band interference; spatial capacity and coverage optimization; Poisson point process

ДИНАМИЧКА АЛОКАЦИЈА НА КАНАЛ ЗА ЕФИКАСНА ОПЕРАЦИЈА НА WiFi-МРЕЖИТЕ ВО СЛОБОДЕН ТВ-ОПСЕГ И ЗАШТИТА НА DVB-T-УСЛУГИТЕ

А п с т р а к т: Појавата на когнитивните радио-технологии за реискористување на недоволно искористените ТВ опсези (TVWSs) претставува потенцијален ризик за деградација на дигиталните видео-радиодифузни (DVB-T) услуги. DVB-T-приемниците треба да бидат заштитени од агрегатната интерференција што се појавува како резултат на активноста на когнитивните технологии во заедничките фреквенциски опсези. Во таа насока, со цел да ги заштитат примарните телевизиски услуги, регулаторните тела јасно ги дефинираат критериумите за пристап на секундарни технологии во слободните телевизиски опсези. Овој труд предлага динамичен и итеративен алгоритам за распределба на канал на уредите на IEEE 802.11af во TVWS, којшто ги распределува каналите врз принцип на максимално растојание. Алгоритамот истовремено има за цел да ги задоволи и критериумите за заштита на DVB-T-услугите поставени од регулаторите, т.е. европскиот Комитет за електронски комуникации (ECC) и американската Федерална комисија за комуникации (FCC). Симулационата анализа на алгоритмот зема предвид реални податоци за моделирање DVB-T-систем и Поасонов точкест процес за моделирање WiFi пристапни точки. Резултатите од симулациската анализа покажуваат значителни добивки во перформансите од аспект на просторниот капацитет и мрежната покриеност на WiFi-мрежите, како и заштитата на DVB-T-услугите.

Клучни зборови: заштита на DVB-T-сервисите; алокација на канал за IEEE 802.11af; агрегатна интерференција; оптимизација на просторен капацитет и мрежна покриеност: Поасонов точкест процес

1. INTRODUCTION

The Digital Video Broadcasting – Terrestrial (DVB-T) standard recently faces serious competition for the (re)use of the TV bands, from other wireless and cellular technologies. The popularity of these bands is owed to the good propagation characteristics and the high percentage of spatially underutilized spectrum. This has resulted in research [1], regulatory [2–8] and standardization efforts for secondary TV White Space (TVWS) systems design, including the recently developed 802.11af standard [9] for WLAN in TVWS, commonly referred also as White-Fi and Super WiFi. However, the introduction of additional wireless technologies in TVWS, leads to interference concerns, especially for the DVB-T receivers. The aggregate interference coming in co-channel basis, remains an open issue for the DVB-T system, resulting in measurement campaigns [10–16] and theoretical studies [17–21] for refinement of spectrum policies for these particular bands.

The WiFi networks can have a substantial performance gain from a sensible and robust channel allocation scheme, in both, classical and cognitive WiFi standards. The channel allocation procedure can aid an efficient management of the WiFi networks and improve their operation in terms of intra- and inter-technology interference mitigation for the IEEE 802.11af networks [22–24]. As the IEEE 802.11af standard is envisioned for WiFi usage of TVWS, it is clear that the DVB-T services, operating on primary basis, need to be adequately protected. The regulations for protection of DVB-T receivers are defined by the regulatory bodies, while the required interfaces and interactions with regulatory databases are provided in the IEEE 802.11af standard. However, up to the best of the authors knowledge, there is a lack of techniques for channel management of the IEEE 802.11af networks that would ensure that the aggregate WiFi interference would not be harmful to primary DVB-T services. These techniques, besides DVB-T protection, should also provide satisfactory WiFi performances via efficient channel allocation based intra-technology interference management.

The main contribution in the paper is a novel algorithm for channel allocation for WiFi (802.11af) operation in TVWS. We consider the Electronic Communications Committee (ECC) [25] and Federal Communications Committee (FCC) [26] regulatory domain operational policies to develop iterative on-the-fly channel allocation scheme, which allocates WiFi channels based on the max distance approach, also considering the aggregate DVB-T interference in the ECC case. The performance assessment of the proposed iterative WiFi channel allocation scheme is based on realistic DVB-T configuration data, and Poisson point process modeling of the WiFi networks. The performances of both approaches, ECC and FCC, are assessed in terms of spatial WiFi capacity distribution and DVB-T pixels degradation. Denote that, in the paper, the term *pixels* refers to *geographical pixels*, i.e. positions of potential receivers.

The paper is organized as follows. Section 2 presents ECC and FCC regulations for TVWS usage and briefly discusses the IEEE 802.11af standard. It also presents the proposed WiFi channel allocation algorithm for TVWS operation and DVB-T coexistence. Section 3 provides the performance assessment of the iterative algorithm for the ECC and the FCC regulatory policies. Finally, Section 4 concludes the paper.

2. COEXISTENCE OF DVB-T AND WiFi IN TVWS

The 802.11af standard (also referred to as White-Fi) for secondary usage of the TVWS, uses the cognitive radio technology to transmit on unused TV channels and provides the required interfaces to limit the interference towards the DVB-T primaries [9]. The re-usage of TVWS bands must comply with regulatory constraints from: FCC (in USA [26]) or ECC (in Europe [25]), for faultless operation of TV services. These regulatory bodies define the required techniques and operational constraints for the cognitive systems in the 470–790 MHz band.

This section gives a technical overview of the two regulatory principles: the FCC based and the ECC based, and targets the possible WiFi deployment in TVWS, describing the basic aspects of the 802.11af standard. The rest of the section presents a newly developed algorithm for TVWS allocation in WiFi based secondary system. The proposed algorithm adopts the constraints defined by the two regulatory domains (FCC and ECC), and thus, provides the adequate protection of the primary DVB-T system. It efficiently allocates an available frequency chunks (1, 2 or 3 continuous TVWS channels) and dynamically manages the aggregate interference generated towards the affected licensed system.

2.1. *Cognitive radio concepts*

Two cognitive radio techniques are used for the efficient determination of available TVWS: the *spectrum sensing* techniques and the *geolocation database* approach for exchange of relevant spectrum access parameters.

The spectrum sensing based approach relies on detection algorithms that identify the presence of primary users (energy, feature detection etc.). The main disadvantage of non-cooperative spectrum sensing is the hidden node problem [1], which contributes to the probability of wrong decision in certain scenarios. This problem can be overcome with cooperative sensing [1] that reduces the detection time and increases the agility and the probability of detection.

The geolocation database operating principles require the ability of the secondary users to perform a geolocalization with certain accuracy. This approach is centralized and the availabilities are determined based on a two way communication between the unlicensed users and the database. Each secondary user that attempts to access the licensed spectrum, sends a request to the database (with its current location) and receives a White Space map or list of available TVWS with the appropriate max operating levels. This approach is particularly suitable for environments with fixed and to some extent invariant primary system characteristics, to ensure a real-time communication without frequent database interactions.

2.1.1. *FCC*

The FCC defined rules that allow unlicensed radio transmitters to operate in the TV broadcast spectrum at locations where that spectrum is not being used by licensed services, as written in technical reports [2–4]. These technical reports provide strategies to prevent harmful interference to incumbent communications services, by introducing protection distances for co-channel and adjacent channel operation of the secondary system. The protection distance is calculated based on the minimum required field strength for efficient operation of the primary system and contains the protection contour and no-talk radius (Table 1) for each DVB-T transmitter.

Table 1

Protection contours and no-talk radius

Height above aver. terrain (HAAT) (m)	No-talk radius (km)	
	Co-channel	Adjacent channel
≤ 3	4	0.4
3−10	7.3	0.7
≥ 10	11.1	1.2

The maximum defined transmit power for the fixed secondary users located outside the protection distances should not exceed 4 W, whereas the portable devices can transmit with a max power of 100 mW. Each secondary user attempting access to the licensed spectrum, first, determines its location with a resolution of 50 m, and afterwards, sends this information to a qualified geolocation database. The geolocation database replies the request, by constructing and providing a list of available TVWS for the particular secondary user location. The provided list has limited time validity and should be updated accordingly at regular time intervals.

2.1.2. *ECC*

The ECC regulation focuses on the definition of implementation strategies for the cognitive radio techniques, which analyze the occupancy of the TV band [5–8]. The protection procedures proposed by ECC consider the geolocation database as a crucial tool for identification and reliable representation of TVWS availabilities. The communication concept considers the *master/slave* categorization of the secondary users. Each *master* device maintains two communication links: one to the list of qualified databases and one for the exchange of relevant information with a particular geolocation database. The *slave* is not involved in a direct communication with the database, but it receives its (encrypted) operating parameters from its *master*.

As part of the European Communications Committee, OFCOM defines the technical requirements for the secondary users that operate in TVWS. Its technical reports divide the secondary users in four emission classes, each identified with a spectral mask and *ACLR* values, as given in Table 2.

Table 2

Adjacent channel leakage ratio (ACLR)

	ACLR

2*n-th adjacent channel	Class 1	Class 2	Class 3	Class 4
$n = \pm 1$	74	74	64	54
$n = \pm 3$	79	74	74	64
$n \geq 3$	84	74	84	74

The ECC implementation methodology provides the required protection for the primary users by maintaining a reasonable *location probability* [5]. The location probability is a radio planning parameter that defines the probability that a DVB-T receiver would operate correctly at a specific geographical pixel. In particular, the ECC methodology defines an in-block and out-block power emission limits for the secondary users to satisfy a certain location probability. The geolocation database provides the relevant information (the list of available channels for the provided geolocation, the maximum permitted in- and out-block powers, the time validity of the generated list and other optional parameters) to the newly registered secondary user. The maximum permitted in-block (P_{IB}) and out-of-block (P_{OOB}) power emission limits are calculated based on the following relations

$$P_{IB} \leq m_z - m_g - PR(\Delta f) - \\ -\sqrt{2}erfg^{-1}\left[2\left(1-\frac{q_2}{q_1}\right)\right]\sqrt{\sigma_z^2+\sigma_g^2}, \\ P_{OOB} \leq P_{IB} - ACLR(\Delta f). \quad (1)$$

In expression (1), m_z and σ_z define the median and the standard deviation of the interference power in the primary system in the absence of secondary users, m_g and σ_g are the median and the standard deviation of the path gain, $PR(\Delta f)$ is the required Protection Ratio for a given frequency offset (Δf), q_1 and q_2 are the location probabilities for the DVB-T service in the absence and presence of one secondary interferer, respectively.

The previously described methodology determines a location based maximum permitted transmit power for each available TVWS channel in the frequency band (470−790 MHz). This methodology is applicable for scenarios with one secondary user. In scenarios with multiple secondary users, the aggregate interference may exceed the permissible interference level and cause degradation to the primary licensed system. Therefore, in order to addresses this problem of aggregate interference, in [8], ECC defines an additional Interference Margin (IM_{dB}) in (2), i.e.

$$P_{IB}^{*} \leq P_{IB} + IM_{dB}, \\ P_{OOB}^{*} \leq P_{IB}^{*} - ACLR(\Delta f). \quad (2)$$

The interference margin takes the interference effects from multiple secondary users into consideration, and can be calculated based on three different methodologies:

Fixed/predetermined *IM* value based on the potential maximum number of interferers N_{mni} at each operational frequency in a given area at the same time, which is defined as:

$$IM_{dB} = 10\log_{10}(N_{mni}).$$

Flexible *IM* value based on the maximum number of active/actual interferers N_{nai}, in a given area operating at the same time, which is defined as:

$$IM_{dB} = 10\log_{10}(N_{nai}).$$

Flexible minimized *IM* value based on the characteristics of each active interferer, registered in the geo-database, at each operational frequency of the secondary user in a given area at the same time. The flexible minimized margin is fitted to correspond to the number of active WSD interferers, and their relative interference nuisance powers, so its calculation engine must check the changes to the number of active WSD interferers in each operational frequency of WSD in cases where i) a new WSD starts operation, ii) an old WSD stops operation and iii) a WSD changes from active state to power-off/powersaving mode.

2.1.3. *IEEE 802.11af standard*

The IEEE 802.11af standard defines international specifications for spectrum sharing among unlicensed secondary users and licensed services in the TV White Space band [9]. It provides a common operating architecture and mechanisms for secondary users to satisfy multiple regulatory domains. The main entities (Figure 1) of an 802.11af network and their functionalities are:

- **Geolocation Database (GDB)** that is authorized and administrated by regulatory authorities. The GDB stores by geographic location, the permissible frequencies and operating parameters for secondary users to fulfill.
- **Registered Location Secure Server (RLSS)** that is a local database, which contains the geographic location and operating parameters for a small number of basic service sets (Basic Service Sets–BSSs). The RLSS distributes the permitted operation parameters to the APs and STAs within the BSSs under the RLSS control.

- **Geolocation-Database-Dependent (GDD) entities** which operation is controlled by an authorized GDB:
  - ***GDD-Enabling*** station (AP), which controls the operation of the stations (STAs) in its serving BSS. It can securely access the GDB to attain the permitted frequencies and parameters in its coverage region. With this information the GDD enabling STA has the authority to allow and control the operation of the STAs under its service, identified as GDD dependent STAs.
  - ***GDD-Dependent*** station, which operation is controlled by the serving GDD enabling STAs. The GDD dependent STAs obtain the permitted operating frequencies and parameters in a form of a WSM (White Space Map) from either the GDD enabling STA or RLSS.

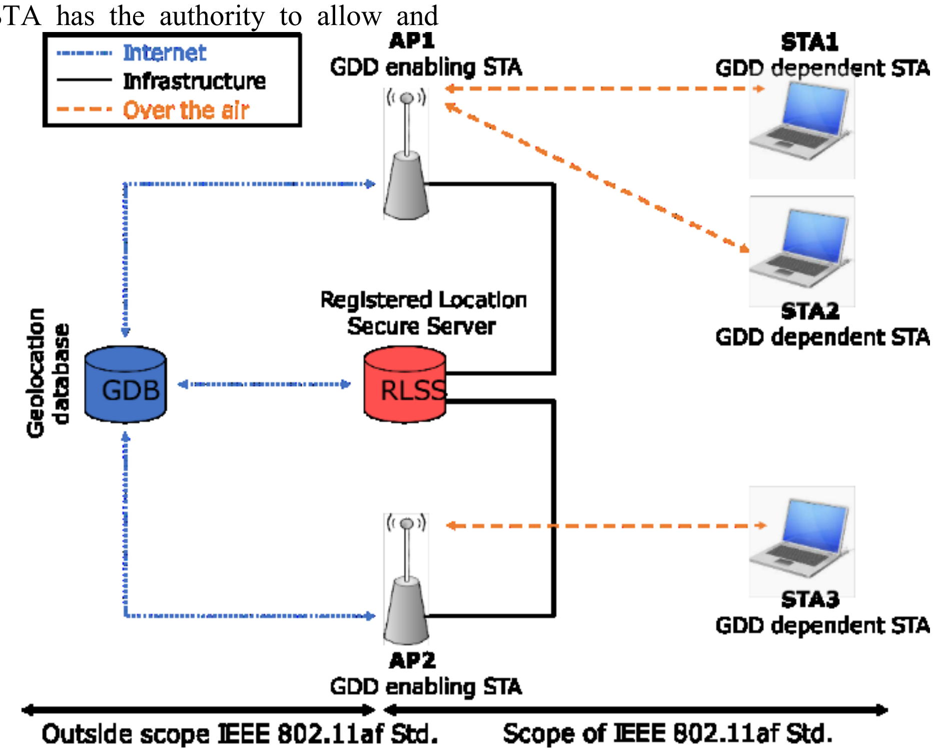


Fig. 1. 802.11af architecture

In the IEEE 802.11af standard, the TV High Throughput (TVHT) Physical Layer (PHY) specification supports single-channel bandwidths or Basic Channel Unit (BCU) W of 6.7 and 8 MHz depending on the regulatory domain. Bonded or non-contiguous bandwidths of 2 W, 4 W, W + W and 2 W + 2 W are also possible, as illustrated in Figure 2.

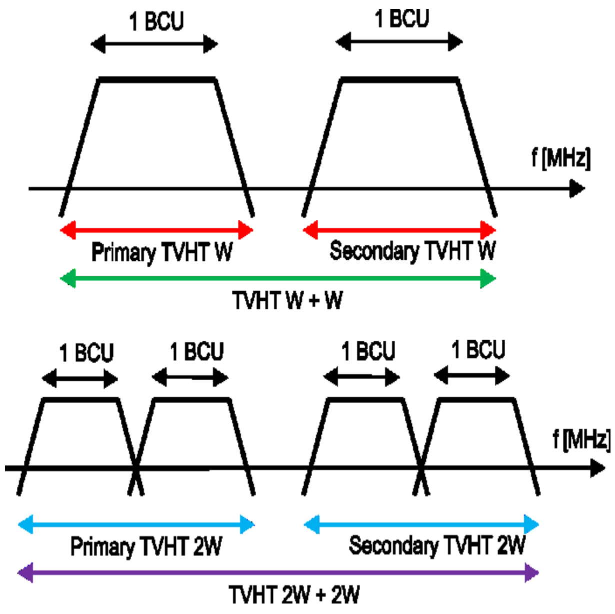


Fig. 2. TVHT channel configurations: *W*, 2*W*, *W*+*W* and 2*W*+2*W*

2.2. *Proposed algorithm for WiFi channel allocation in TVWS*

Each secondary user, prior to the transmission, queries for TVWS availabilities in its surrounding environment, i.e. performs the *Channel Availability Query (CAQ) procedure*. With this procedure, the secondary user retrieves a TV White Space Map, which contains the available TVWSs along with the appropriate maximum permitted operating parameters. Moreover, the SU sends a request to the local geolocation database (or Channel Schedule Management (CSM) procedure) to obtain the time validity information of the acquired TVWS Map. Based on these procedures, the SU gets a clear representation of its radio environment and becomes eligible for initiating operation in a TVWS channel from the list of available TVWSs.

For efficient interference management, the geolocation database should be able to perform a dynamic estimation of the interference generated from the secondary users into the licensed DVB-T services. In this paper, we propose an iterative algorithm for TVWS channel selection, which adopts the requirements of the two regulatory domains: FCC and ECC. The assumed system model comprises WiFi network deployment with *M* access points, exploiting 1 (8 MHz), 2 (16 MHz) or 3 (24 MHz) continuous and non-overlapping TVWS. The proposed algorithm uses the geolocation database operating principle and allocates a frequency chunk for the secondary user attempting access in the TVWS spectrum. For the FCC scenario, the algorithm solely provides efficient TVWS admission control. In the ECC based scenario, the developed algorithm introduces an additional interference management procedure (despite the TVWS admission control), that exploits the same logic as the methodology for derivation of the flexible minimized *IM* value, described in Section 2.1.2.

Figure 3 describes the algorithm for frequency channel selection from a set of available channels **A**, based on the two approaches, FCC and ECC. The availability set **A** comprises the frequency channels where the maximum allowed *EIRP* is greater than or equal to 20 dBm, according to the FCC and ECC calculation methods. In each iteration *k*, for the newly registered secondary user *k*, the algorithm determines the set of the available channels **A**(*k*) and keeps track of the previously allocated channels in a busy channels set $\mathbf{A}_{\mathbf{busy}}(k)$. If the availability set contains multiple TVWS channels that have not been allocated (not in the busy set $\mathbf{A}_{\mathbf{busy}}(k)$, the FCC approach *randomly* allocates an operation channel *ch* for the user *k*, whereas the ECC based approach allocates a channel *ch* based on the *maximum permissible transmit power* for the reported location of the user *k*. In particular, the algorithm constructs a set **S**(*k*), containing the closest neighbors that operate on each of the channels in **A**(*k*) and selects an operating channel *ch* based on the max distance between the user *k* and the users in the set **S**(*k*). In case of aggregation of two or three continuous white space channels (frequency chunks), the frequency allocation decision is based on the minimum interference level over the total availability set.

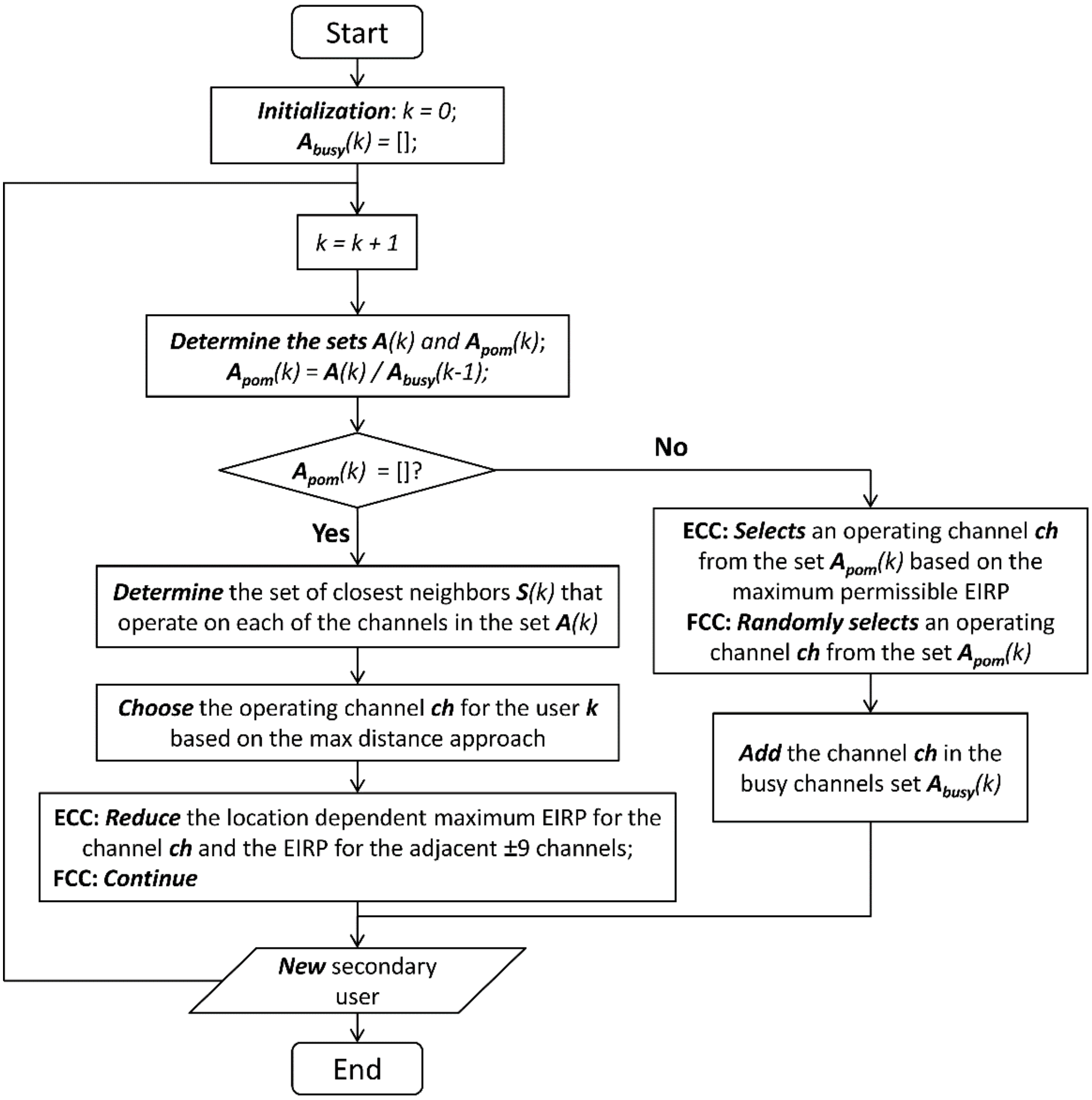


Fig. 3. Flowchart algorithm description

The algorithm allocates the operating channels in an iterative manner, while dynamically maintaining the channel availability. Moreover, since the ECC method derives a location dependent maximum *EIRP*, the algorithm performs an iterative reduction of the maximum allowed *EIRP* for the allocated channel *ch* and the adjacent ±9 channels, based on the calculated coupling gain (the received power = the user k transmit in-block/out-block power + the propagation gains) between the location of the user k and the total evaluated pixels in the targeted territory.

3. PERFORMANCE ANALYSIS

This section presents the performance analysis of the proposed on-the-fly algorithm for WiFi channel allocation in TVWS scenarios. The investigated scenario considers M WiFi access points, distributed randomly in the target area. For the distribution of the APs, we use the Geyer saturation process [27] (a generalization of the Strauss process), in order to simulate WiFi positions in urban areas. The evaluation area targets the territory of Skopje (Figure 4) with dimensions 15 × 19.5 km and a pixel size of 30 × 30 m. The WiFi channel gains incorporate the losses predicted by Okumura-Hata urban model with $PLC = 3.5$, with AP antenna height of 10 m, 0 dB gain, whereas the considered bandwidths are: 8, 16 and 24 MHz.

The DVB-T system modeling is based on the Longley-Rice propagation model along with terrain effects to predict the received DVB-T signal strength. It exploits relevant operating parameters obtained from the Agency for Electronic Communications of the Republic of Macedonia. After the generation of the DVB-T coverage maps, the simulation analysis determines the available TVWS based on the FCC and ECC calculation methods and applies the proposed algorithm for frequency allocation for the WiFi access points. All simulation results are obtained over 1000 Monte Carlo trials.

Fig. 4. Skopje city map

Figure 5 illustrates the location dependent number of available TVWSs according to the ECC methodology. On opposite, the list of available TVWSs, based on the FCC methodology comprises the following DVB-T channels: {25, 29, 31, 35, 44, 48, 51, 53, 58, 59, 60}. In case of aggregating 2 (3) continuous and non-overlapping channels, the ECC approach produces 3 (1) available frequency chunks, whereas the number of available chunks based on the FCC approach is 2 (1).

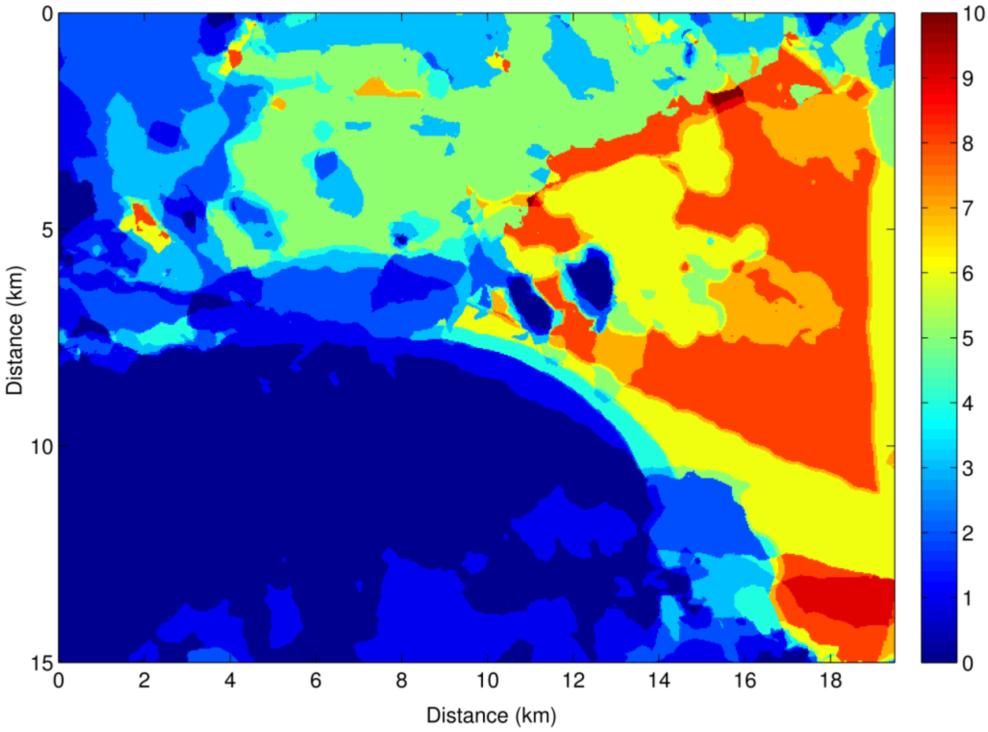


Fig. 5. Location dependent number of available TVWS

Figure 6 presents the distribution of the max capacity per pixel, considering the total set of available channels. The depicted curves compare the performances of the proposed algorithm for frequency allocation with the case of a random assignment of available frequency channels. They reveal the gain in capacity in both approaches (FCC and ECC) since the developed algorithm enables the efficient management of the co-channel interference. For this particular scenario, the FCC approach provides the greater TVWS availability and, thus, the bigger capacity ranges compared to ECC. Additionally, the depicted pdfs have a peak value around zero for the ECC case, due to the existence of geographical locations with no TVWS channels available. The FCC approach provides better secondary performances, due to the less restrictive policies, i.e. due to the using of no talk zones, rather than aggregate interference limits.

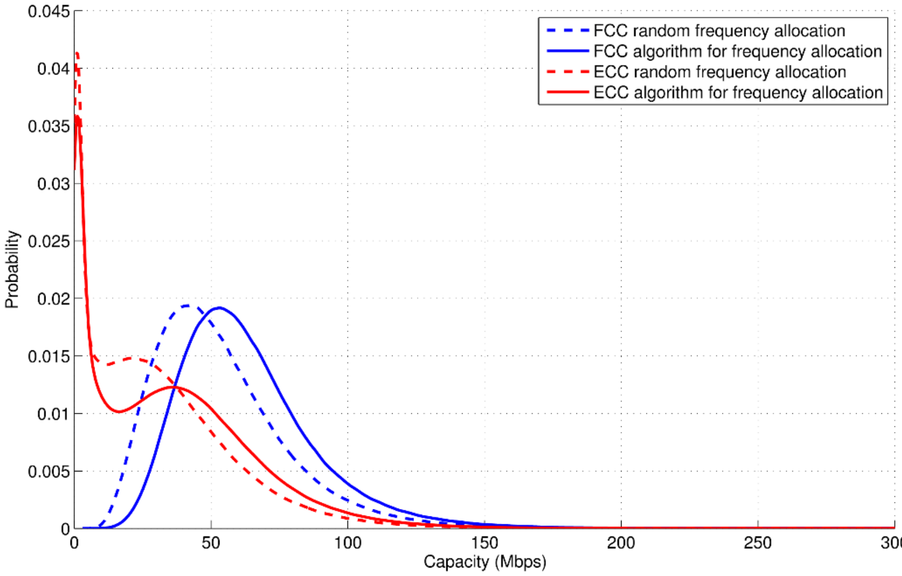
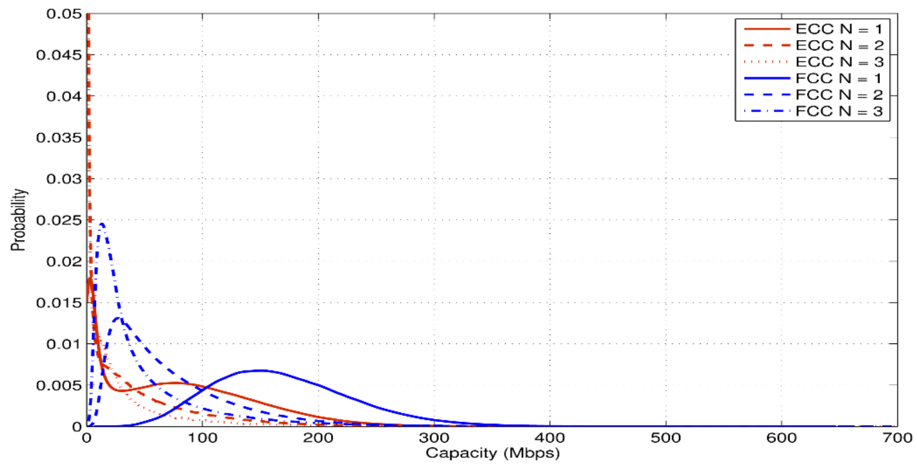


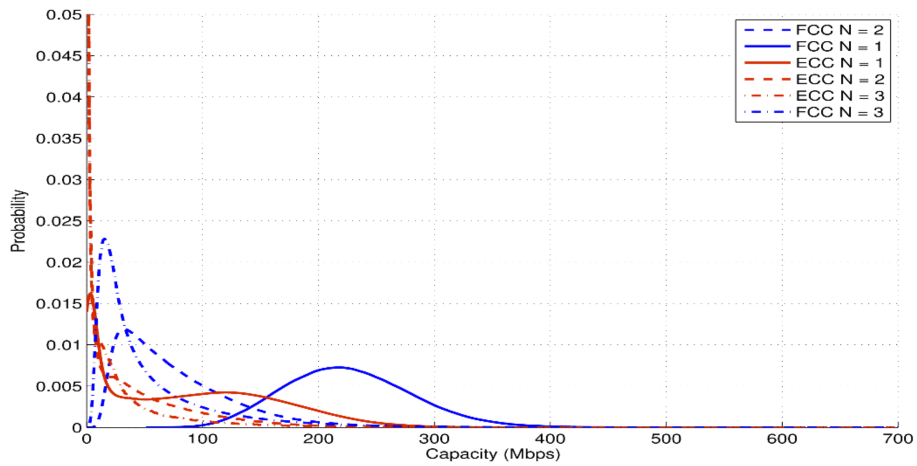
Fig. 6. PDF of the max capacity per pixel (over the total number of WiFi operating TVWS channels)

Figure 7 depicts the pdfs of the sum capacity per pixel for two different APs densities and three different bandwidths (1, 2 and 3 continuous and non-overlapping TVWS channels). The curves show the full pdf of the sum capacity per pixel, so the shift of the pdfs to the right indicates that higher capacity values are more probable, meaning that higher sum capacity values will be achieved. The presented pdfs prove that the proposed algorithm for one TVWS channel allocation enables the efficient aggregate interference management, resulting in higher capacity values with the increase of the APs density. In case of aggregating 2 (3) continuous and non-overlapping TVWS channel, the capacity gain becomes negligible as the APs density rises, due to the low availability of the aggregated frequency blocks. In this particular case, the proposed algorithm controls the generated interference dynamically adjusting the maximum permitted transmit power (for the ECC approach), thus, restricting the access of certain secondary users.

Figure 8 presents the max, mean and min coverage range of the WiFi based secondary system. It compares the two approaches, FCC and ECC, and evaluates the algorithm for the allocation of one, two or three aggregated and continuous frequency channels (TVWS). The curves in Figure 8a reveal that the utilization of one TVWS channel produces the greater coverage ranges, because of the highest TVWSs availability. On the other hand, the usage of wider frequency bands by aggregating 2 (3) continuous and non-overlapping channels, reduces the coverage range, due to the low availability of these particular frequency blocks and, thus, the dominance of the co-channel interference. Finally, the last investigated case (Figure 8c) proves that when both approaches, FCC ans ECC, allocate of 3 aggregated continuous and non-overlapping channels, the ECC methodology in the developed algorithm ensures more efficient interference management and protection of the licensed services.

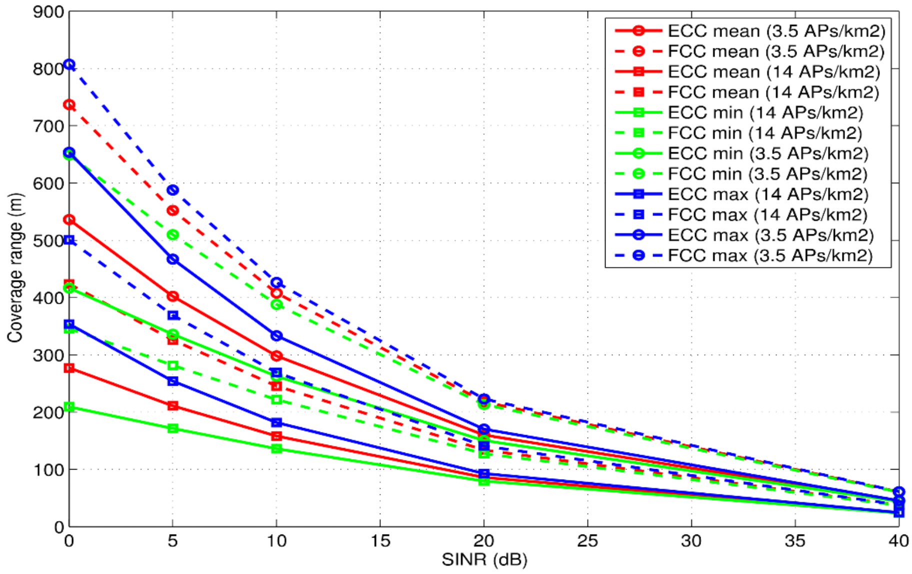


(a) Number of APs per km^2 = 3.5

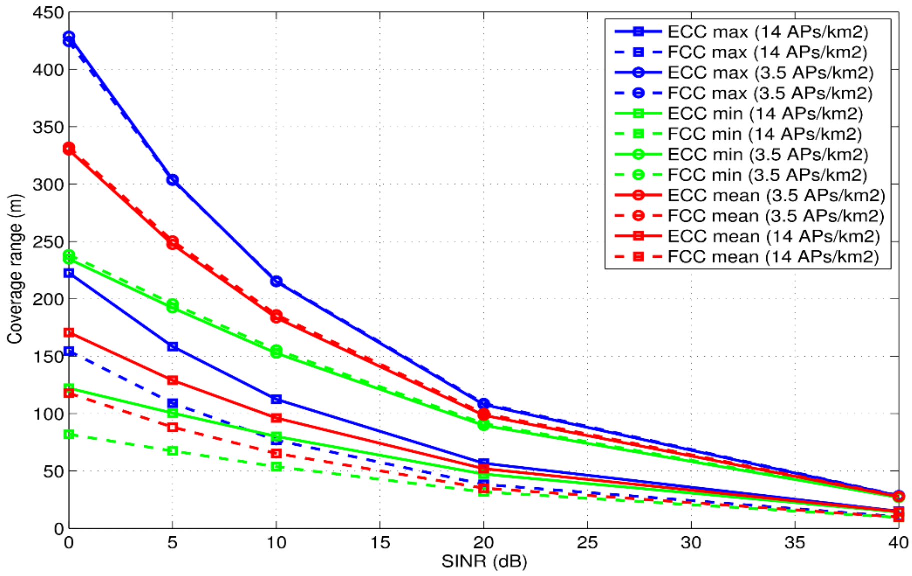


(b) Number of APs per km^2 = 14

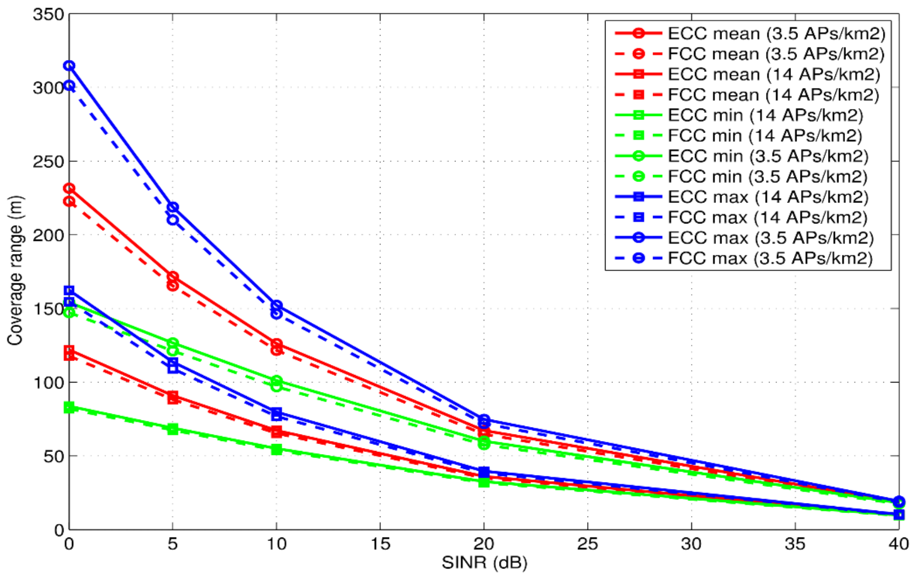
Fig.7. Probability density function of the sum capacity per pixel



(a) $N = 1$ (1 W)



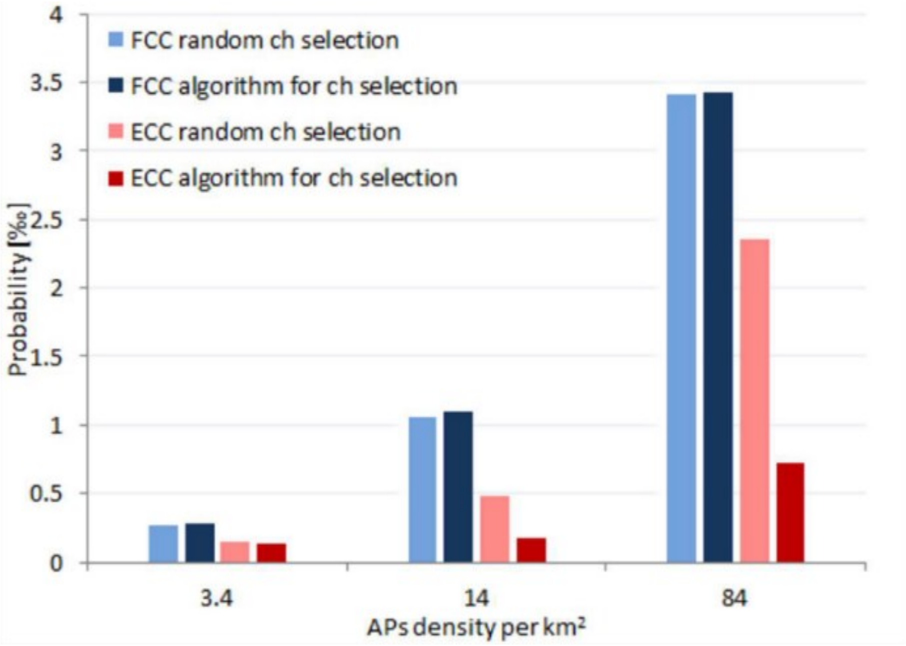
(b) $N = 2$ (2 W)



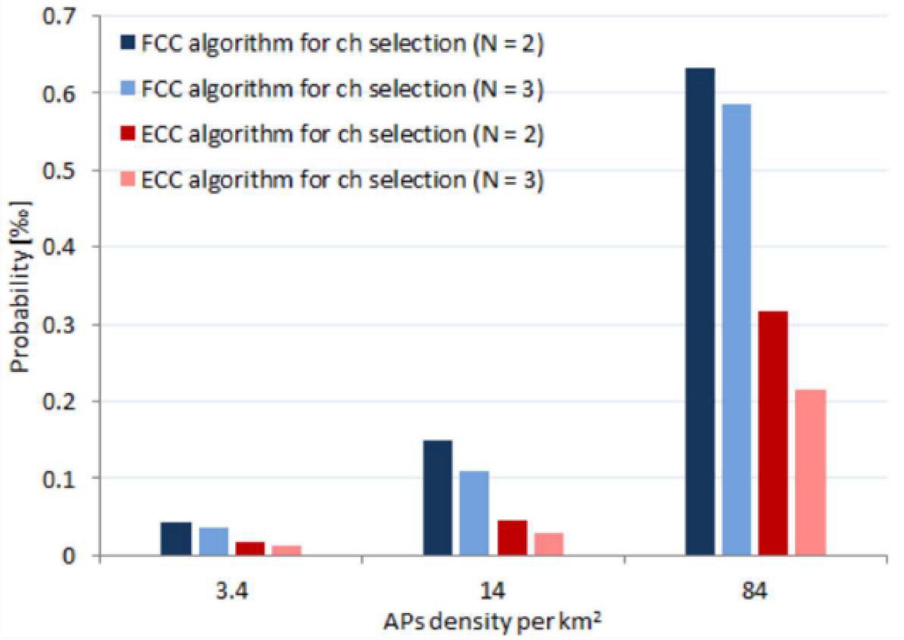
(c) $N = 3$ (3 W)

Fig. 8. Coverage range for WiFi based secondary user

Figure 9 depicts the permillage of pixels where the interference level exceeds the maximum interference budget (I_{max}) [16]. This value is calculated based on the co-channel protection ratio for DVB-T services, which equals 21 dB [5]. For the derivation of the results in Figure 9, only the most critical pixels are considered (the pixels located at the edge of the coverage area of each DVB-T transmitter, i.e. the locations with received DVB-T signal strength in the range −85 to −75 dBm). The depicted figure reveals the effect of the WiFi APs density on the probability of interference degraded pixels. It also confirms the capability of the proposed algorithm for frequency allocation (adopting both the FCC and ECC based approaches) to provide the adequate protection of the primary system. Evidently, better DVB-T service protection is provided in the case of the ECC approach.



(a) $N = 1$ (1 W)



(b) $N = 2$ (2 W) vs $N = 3$ (3 W)

Fig. 9. Permillage (‰) of pixels with interference level ≥ $I_{max} = -106$ dBm

4. CONCLUSION

The DVB-T services have to be protected from aggregate in-band coming from cognitive technologies arising in the TV bands. The DVB-T protection criteria defined by the regulatory bodies should be satisfied by novel cognitive technologies (IEEE 802.11af) operating in TV White Spaces. Therefore, there is an evident necessity for techniques that simultaneously optimize the operation of these networks and provide unobstructed operation of DVB-T services. This paper deals with such scenario. It proposes an iterative on-the-fly channel allocation algorithm for IEEE 802.11af operation in TV White Spaces, allocating the WiFi channels based on the max distance approach, satisfying DVB-T protection criteria from the ECC or the FCC regulatory bodies. The simulation analysis of the algorithm uses realistic DVB-T data and stochastic modeling of WiFi networks. The simulation results reveal significant gains in terms of increased spatial capacity/coverage and reliable DVB-T protection.

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