Wi-Fi, but not on Steroids: Performance Analysis of a Wi-Fi-like Network Operating in TVWS under Realistic Conditions

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Abstract*—The recent decisions by regulators in the USA and UK to open up unused portions of UHF spectrum for secondary use have been met with keen interest in using these TV white spaces (TVWS) for providing broadband services through Wi-Fi-like connectivity. Amid the ensuing media hype about "Wi-Fi on steroids", there is a widespread perception that Wi-Fi operating in TVWS will provide much longer range, superior speeds, and more reliable connections than traditional Wi-Fi at 2.4 GHz. In this paper, we present a quantitative analysis of the performance of a network of Wi-Fi-like access points (APs) operating in TVWS in order to obtain a realistic estimate of the achievable range and downlink rate of such a secondary system. Unlike previous studies, we explicitly consider the effects of inter-AP interference and congestion and use real TVWS channel availability estimates from an example region of Germany. We confirm the favourable properties of the lower TVWS frequency range, of enabling better propagation through walls and a larger coverage range for the same power budget. Our results show that operating Wi-Fi hotspots in TVWS might be technologically attractive for outdoor rural areas where user demand is low. However, the extended coverage range in TVWS leads to increased congestion which rapidly limits the system capacity for an outdoor urban deployment with high user density. Therefore, a combined technological and economical analysis is essential before any final judgement can be reached about the viability of large-scale Wi-Fi deployments in TVWS.

I. Introduction

White spaces in the TV bands have drawn a lot of attention as they provide valuable spectrum for secondary use by cognitive radio devices and have the potential to enable long-range wireless broadband access and new wireless applications and services. In September 2010, the Federal Communications Commission (FCC) released revised rules regarding access to the unused portions of the UHF spectrum in the USA [1]. Recently Ofcom has also allowed secondary use of the TV bands for wireless broadband services in the UK [2]. So far industry and standardisation bodies have shown a particular interest in using the TV white spaces (TVWS) for providing rural areas with broadband services through extended Wi-Fi-like connectivity popularly known as "super Wi-Fi" or "Wi-Fi on steroids" [3], [4]. Several ongoing trials by individual companies as well as industry consortia are attempting to demonstrate that unused TV bands can increase the bandwidth available for mobile broadband access. For example, the recently established Cambridge TV White Spaces Consortium aims at exploring how the unused TV bands can provide inexpensive solutions to satisfy the demand for wireless broadband connectivity in the UK [5]. In [6] Microsoft reported on the design and implementation of their "WhiteFi" network, one of the first prototyping efforts of a Wi-Fi-like wireless system in TVWS. The IEEE 802.11af working group has also been set up to define a standard for implementing Wi-Fi-like networks in TV bands [7].

Generally, there is a strongly held belief that operating Wi-Fi in TV bands will provide greater speeds, longer range, and more reliable connections [3]. This view has been encouraged by initial studies into the potential of Wi-Fi-like secondary systems in TVWS, based on the possibly naive assumption that a sufficiently large amount of TVWS spectrum is available [8]–[11]. For example, the authors in [9]–[11] base their assessment of the downlink capacity of a secondary Wi-Fi-like network on the conclusion that "ample" TVWS is available (itself based on an estimate of 150 MHz of TV spectrum being available on average throughout the UK). These results must be interpreted with caution, as in practice it is imperative to consider *which* fraction of the population has access to the available TVWS spectrum (e.g. urban vs. rural) and how severely the spectrum is fragmented. Most crucially, under the simplistic assumption of "sufficient" and "ample" TVWS availability, previous studies fail to take into account the effects of channel congestion in TVWS arising from Wi-Fi-like operation of multiple secondary devices. As a consequence of adopting such an oversimplified system model, prior estimates of the achievable capacity of a Wi-Fi-like secondary system in TWVS tend to be overly optimistic.

In this paper, we analyse the performance of a network of Wi-Fi-like access points (APs) operating in TVWS in order to obtain a realistic estimate of the achievable range and downlink rate of such a secondary system. We take into account real TVWS channel availability estimates, calculated for a region of Germany. Unlike previous studies, we also consider inter-AP interference in terms of CSMA contention effects and analyse congestion arising from multiple nearby APs sharing the same channel. We confirm that operating in the lower TVWS frequency band (vs. ISM at 2.4 GHz)

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TABLE I
SYSTEM MODEL PARAMETERS FOR DIFFERENT DEPLOYMENT SCENARIOS

	Outdoor Urban	Indoor Urban	Outdoor Rural
Study area	2 km x 2 km	500 m x 500 m	5 km x 5 km
AP density, λ	12.5/km^2	125/km^2	0.25/km^2
Propagation model	k = 3	k = 4, 18 dB wall loss	k = 2.5

has attractive features such as providing a somewhat larger coverage area with the same power budget and allowing better penetration through walls. However, we emphasize that operating in TVWS does not offer any more capacity compared to traditional Wi-Fi (as maximum downlink rates are simply proportional to the channel width), downplaying the media-hype claims of "super Wi-Fi" offering speeds far superior to those of present Wi-Fi. On the contrary, we demonstrate that the increased coverage range of Wi-Fi-like APs operating in TVWS leads to increased congestion and correspondingly lower downlink rates for many deployment scenarios.

The remainder of this paper is organised as follows. In Section II we describe our network and propagation models. In Section III we discuss TVWS availability. In Section IV we detail our modelling of inter-AP interference and the estimated downlink throughput of a secondary AP. In Section V we present and analyse simulation results of the performance of a Wi-Fi-like secondary network in TVWS for various deployment scenarios. In Section VI we present our conclusions.

II. SYSTEM MODEL

A. Network Model

We model the location of secondary APs using a homogeneous Poisson point process with density λ. We consider three potential deployment scenarios for the secondary network: (i) outdoor urban, (ii) indoor urban, and (iii) outdoor rural. We consider APs located within a study area of 2 km by 2 km, 500 m by 500 m, and 5 km by 5 km for the respective scenarios. Throughout this paper, we take the city of Aachen and the area around Wipperfürth in the Southern Rhineland region of Germany as examples of an urban and rural area, respectively, where the secondary network might be deployed. For the outdoor urban scenario, we assume an AP density of λ = 12.5 APs/km^2 based on the population density of 6250 people/km^2 in central Aachen (as obtained from the Landscan [12] data set, 2006 release) and an assumption of one outdoor hotspot (AP) per 500 people. For the outdoor rural scenario, we assume an AP density of λ = 0.25 APs/km^2, corresponding to the population density of around 125 people/km^2 in the Wipperfürth area. For the indoor urban scenario, we assume an AP density of λ = 125 APs/km^2 (based on an assumption of one AP per 50 people); this is comparable to the density of Wi-Fi APs measured in an urban centre such as Atlanta or Las Vegas [13]. Fig. 1 illustrates an example network realisation (generated using the **spatstat** [14] package in R [15]) for the outdoor urban scenario. The system model parameters characterising each scenario are summarised in Table I.

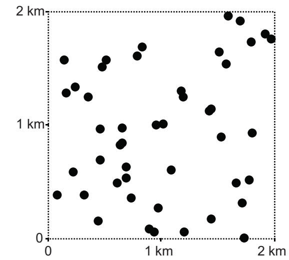


Fig. 1. Example secondary network realisation for the outdoor urban deployment scenario, showing random AP locations as generated using a Poisson point process with density λ = 12.5/km^2.

B. Propagation Model

We assume the log-distance path loss model, which gives the average path loss L at a transmission distance d as

$$L = L_{ref} d^k, \tag{1}$$

where L_{ref} is the path loss at the reference distance of 1 m and k is the path loss exponent [16]. The reference path loss may be calculated using the free space path loss formula,

$$L_{ref} = \frac{(4\pi)^2 d_{ref}^2 f_c^2}{c}, \tag{2}$$

where the transmitter and receiver antennas are assumed to have unity gain, d_{ref}=1 m, c is the speed of light, and f_c is the carrier frequency. To keep our analysis tractable, we set f_c = 630 MHz for secondary APs operating in TVWS (centre of the 470-790 MHz frequency band corresponding to DVB-T channels 21-60), regardless of the actual TV channel the secondary transmitter occupies. Throughout our analysis we compare the performance of the secondary Wi-Fi-like system operating in TVWS to that of the existing IEEE 802.11g Wi-Fi [17] operating in the f_c = 2.4 GHz ISM band. We characterise the considered deployment scenarios by the associated typical values of k, as detailed in Table I. For the indoor urban scenario, we assume an additional wall penetration loss of 18 dB (an average of 3 obstructing walls with 6 dB loss each).

III. TVWS CHANNEL AVAILABILITY

The amount of TVWS available for secondary operation varies between different countries and regions [18]. In our analysis, we use TVWS channel availability estimates for the Southern Rhineland region of Germany from [19] (based on the European draft SE43 protection rule [20]) as one realistic and rather typical example of TVWS availability[1]. Fig. 2 illustrates the number of unprotected TV channels available over the Southern Rhineland region. The underlying data set from [19] reveals that channels {21, 22, 30-32, 39-48, 56, 60} and {21, 23, 24, 32, 34, 38, 39, 41, 42, 44, 45, 47,

[1]Importantly, we do so without loss of generality; if we were to instead consider a different geographic region or protection rule (e.g. FCC [1]), although our specific quantitative results would change, the qualitative trends and conclusions emerging from our analysis would not be significantly different.

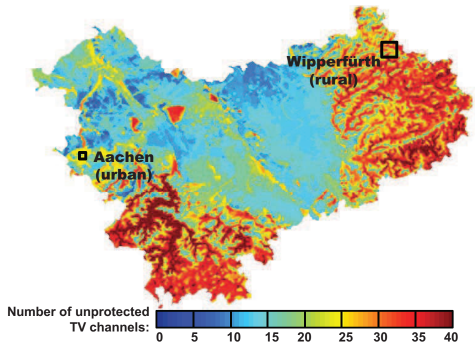


Fig. 2. Map of Southern Rhineland in Germany showing estimated TVWS availability (reproduced from [19]), marked with the location of the 2 km by 2 km Aachen urban area and the 5 km by 5 km Wipperfürth rural area.

51, 54} are predicted to be available in every pixel of the urban Aachen and rural Wipperfürth study area, respectively. We assume APs in the secondary network operate on fixed-width non-overlapping channels, the availability of which is advised by a database. In line with existing proposals for Wi-Fi operating in TVWS [7], we allow channel aggregation, of up to three 8 MHz TV channels. For reasons of practical implementation feasibility, we assume only adjacent channels may be aggregated. Consequently, in our analysis we consider the following channel availabilities: seventeen 8 MHz channels *or* seven 16 MHz channels *or* four 24 MHz channels, for the urban scenario; and fourteen 8 MHz channels *or* four 16 MHz channels, for the rural scenario. For reference, IEEE 802.11g Wi-Fi has three non-overlapping 20 MHz channels [17].

IV. AP Interference & Estimated Throughput

We consider a network of Wi-Fi-like secondary AP transmitters operating in TVWS, using the CSMA/CA MAC protocol. To keep our analysis tractable, we assume traffic is downlink and saturated and consider a single user per AP[2]. We adopt the model proposed in [21] to estimate the downlink throughput when interference from other co-channel APs in the network is taken into account, as elaborated in this section.

A. Coverage Model

Let $\rho(\beta)$ be the auto-rate function which maps the raw bit rate ρ provided by an AP to a user for a given minimum received SINR (signal to interference-plus-noise ratio) value β. We assume that the auto-rate function $\rho(\beta)$ is a piecewise constant function, as detailed in Table II for different secondary channel bandwidths, based on the spectral efficiency and minimum receiver sensitivity specifications in the IEEE 802.11g standard [17]. Let $SINR_{u,x}$ be the SINR at user u associated with AP x. User u is said to be β_n-covered by AP x if $SINR_{u,x} \geq \beta_n$, whereby user u obtains a raw data rate of at least ρ_n. We assume that an AP will provide the highest possible raw data rate to a user as allowed by its

[2]Our analysis thus represents a best-case estimate of the capacity of a secondary Wi-Fi network in TVWS; in reality a single AP would likely support multiple users and the capacity per user would be reduced accordingly.

TABLE II
Definition of $\rho(\beta)$ auto-rate function, consistent with IEEE 802.11g specifications

Index, n	Spectral efficiency[a] (bps/Hz)	Minimum SINR, β_n (dB)	Raw bit rate, ρ_n (Mbps)			
			20 MHz channel (802.11g)	8 MHz channel (TVWS)	16 MHz channel (TVWS)	24 MHz channel (TVWS)
1	0.3	4	6	2.4	4.8	7.2
2	0.45	5	9	3.6	7.2	10.8
3	0.6	7	12	4.8	9.6	14.4
4	0.9	9	18	7.2	14.4	21.6
5	1.2	12	24	9.6	19.2	28.8
6	1.8	16	36	14.4	28.8	43.2
7	2.4	20	48	19.2	38.4	57.6
8	2.7	21	54	21.6	43.2	64.8

[a]For modulation, coding rate: BPSK, 1/2; BPSK, 3/4; QPSK, 1/2; QPSK, 3/4; 16-QAM, 1/2; 16-QAM, 3/4 ; 64-QAM, 2/3; 64-QAM, 3/4.

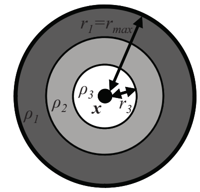


Fig. 3. Illustration of auto-rate function $\rho(\beta)$, whereby AP x provides a raw bit rate of ρ_n to a user located within a range of r_n (only showing up to $n = 3$ for the sake of clarity); the maximum coverage range r_{max} corresponds to the boundary of the coverage area (cell) of AP x.

SINR, i.e. the rate is equal to ρ_8 if $SINR_{u,x} \geq \beta_8$, ρ_7 if $\beta_7 \leq SINR_{u,x} < \beta_8$, etc. If $SINR_{u,x} < \beta_1$, user u is not covered by AP x (i.e. the rate is equal to 0).

The coverage area (cell) of AP x is thus defined as the set of user locations $\boldsymbol{U_x}$ for which $SINR_{u \in \boldsymbol{U_x},x} > \beta_1$. Correspondingly, the maximum (cell-edge) coverage range of AP x, r_{max}, is the mean distance from AP x to users located on the contour for which $SINR_{u,x} = \beta_1$, as illustrated in Fig. 3. Analogously, we define r_n to be the maximum range corresponding to a given raw rate ρ_n (such that r_{max}=r_1). It should be noted that the contours representing the β_n-coverage boundaries of AP x are depicted as circles in Fig. 3 only for ease of illustration; their actual shape depends on the relative position of other interfering co-channel APs.

B. Interference Model for Co-Channel APs

Let $\boldsymbol{A}$ be the set of all secondary AP transmitters in the network, and $\boldsymbol{A^j}$ be the subset of all APs in the network operating on channel j, where $j = \{1, 2, 3, ..., J\}$ is the index of each of J available non-overlapping channels. Let $\boldsymbol{A_x^j}$ be the set of all co-channel APs which are in the contention domain of AP x. A pair of co-channel APs are considered to be in a common contention domain if they receive each other's signal with power greater than the carrier-sensing detection threshold[3]. As per the CSMA/CA MAC protocol, an AP

[3]Specifically, co-channel APs x and y share a contention domain if $SNR_{x,y} \geq \beta_1$, as per the IEEE 802.11 specification [17].

will refrain from transmitting if another AP in its contention domain is already transmitting (i.e. when AP x is transmitting, all other APs in the set $\boldsymbol{A_x^j}$ will refrain from doing so). It follows that the set of APs which cause interference during the transmission of AP x are those APs which operate on the same channel as AP x but are outside its contention domain[4]. Thus, the SINR at user u associated with AP x is given by

$$SINR_{u,x} = \frac{P_{tx}(L_{u,x})^{-1}}{N_0 + I_{PU} + \sum_{y \in \boldsymbol{A^j} \setminus \boldsymbol{A_x^j}} P_{tx}(L_{u,y})^{-1}}, \quad (3)$$

where P_{tx} is the transmission power of the secondary AP (assumed in our analysis to be fixed across all APs in the network), $L_{u,x}$ represents the average path loss on the link between transmitter x and receiver u (as given by (1)), N_0 is the noise power at the receiver, and I_{PU} is the interference power from the primary user (DVB-T) transmitter at the secondary user receiver. We make the conservative assumption of maximum interference from the DVB-T system, setting I_{PU} equal to the received power of -87.5 dBm corresponding to the primary user protection contour [19].

Let M_x be the fraction of time that AP x is granted channel access by the CSMA/CA MAC protocol. If AP x has other APs in its contention domain (i.e. if $\boldsymbol{A_x^j} \neq \varnothing$), the other APs will also be contending for access to the shared wireless medium, and the channel access time of AP x will be $M_x < 1$. Consequently, the downlink throughput of a user u associated with AP x may be estimated as

$$R_{u,x} = M_x \rho(SINR_{u,x}), \quad (4)$$

where $\rho(SINR_{u,x})$ is the raw data rate provided to user u by AP x, as per the auto-rate function $\rho(\beta)$. Assuming fair channel access, the channel access time of an AP is approximately equal to the inverse of the number of APs in its contention domain. The fraction of time that AP x is granted channel access by the CSMA/CA MAC protocol is given by

$$M_x \approx \frac{1}{|\boldsymbol{A_x^j}|}, \quad (5)$$

where $|\boldsymbol{A_x^j}|$ is the total number of APs in the contention domain of AP x (i.e. the size of set $\boldsymbol{A_x^j}$). Therefore, (4) may be re-expressed as

$$R_{u,x} = \frac{\rho(SINR_{u,x})}{|\boldsymbol{A_x^j}|}. \quad (6)$$

Fig. 4 illustrates our inter-AP interference model, for the case of all APs being co-channel (simulation result generated as described in Section V).

V. Simulation Results & Analysis

In this section we present simulation results of the performance of a secondary Wi-Fi-like network in TVWS for our considered deployment scenarios. The results were obtained

[4]This is a modification of the model from [21], where interference from APs outside the contention domain of AP x is not considered.

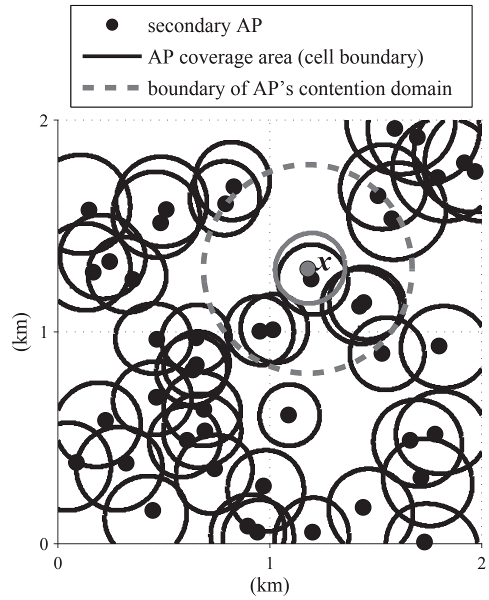


Fig. 4. Illustration of inter-AP interference (all APs co-channel, outdoor urban scenario with P_{tx} = 30 dBm and 24 MHz channel in TVWS). As per CSMA/CA, the eight APs inside the contention domain of AP x reduce its channel access time to one ninth, whereas the remaining APs cause interference during its transmission (reducing the coverage range of AP x by decreasing the SINR of an associated user).

via MATLAB simulations by considering user terminal locations on an evenly spaced grid[5] over the secondary network study area and calculating the downlink throughput obtained at each potential user location for each AP in the network, thereby determining the coverage area of each AP and the downlink rate for an associated user within its cell. Specifically, the estimated downlink throughput for a user randomly located within the cell of AP x is given by

$$\overline{R}_x = \frac{1}{|\boldsymbol{U_x}|} \sum_{u \in \boldsymbol{U_x}} R_{u,x}, \quad (7)$$

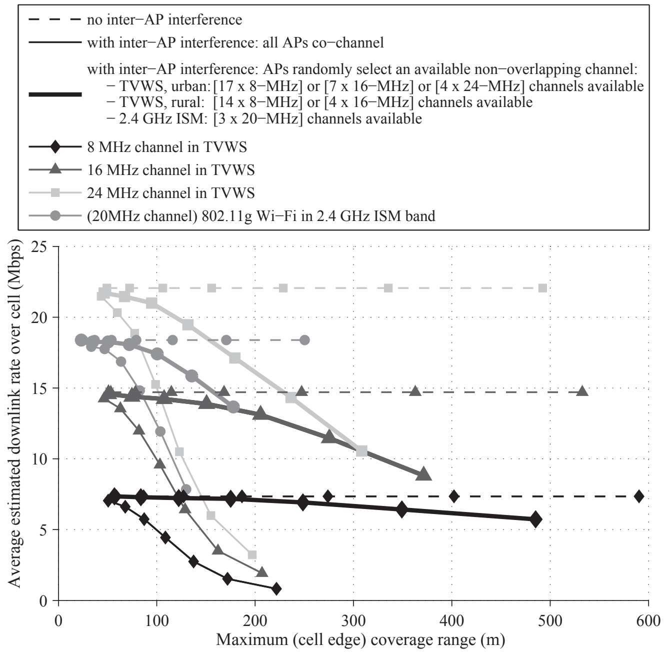
where $R_{u,x}$ is given by (6) and $\boldsymbol{U_x}$ is the set of user locations on the sampling grid which are covered by AP x. The mean estimated downlink rate over the whole network of $|\boldsymbol{A}|$ APs is then given by

$$\overline{R}_{\boldsymbol{A}} = \frac{1}{|\boldsymbol{A}|} \sum_{x \in \boldsymbol{A}} \overline{R}_x. \quad (8)$$

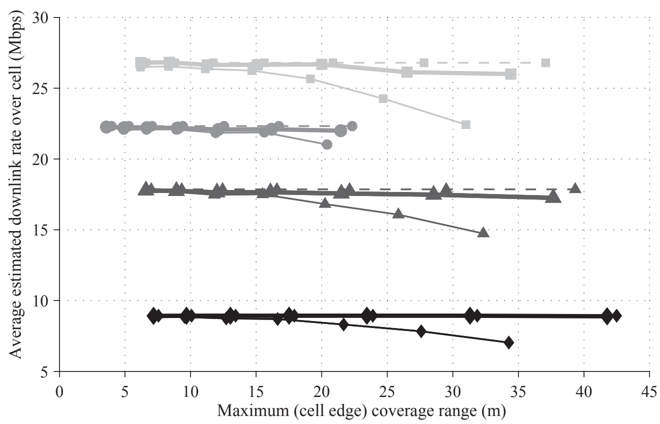
The mean cell-edge (maximum) AP coverage range over the network, $r_{max}^{\boldsymbol{A}}$, is defined analogously.

Fig. 5 presents simulation results of $\overline{R}_{\boldsymbol{A}}$ versus $r_{max}^{\boldsymbol{A}}$ for each deployment scenario, for different secondary channel widths (averaged over 5 random network realisations). Results for TVWS operation are presented alongside IEEE 802.11g Wi-Fi at 2.4 GHz for reference. Each curve in Fig. 5 was generated by varying the transmission power of the secondary APs, $P_{tx} = \{0, 5, 10, 15, 20, 25, 30\}$ dBm. The dashed curves

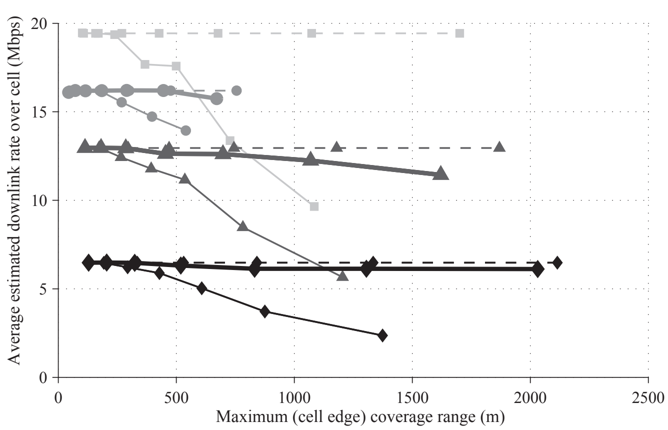
[5]Grid resolution of 4 m, 1 m, and 10 m was used for the outdoor urban, indoor urban, and outdoor rural scenario, respectively.



(a) Outdoor urban scenario



(b) Indoor urban scenario



(c) Outdoor rural scenario

Fig. 5. Average estimated downlink rate for a covered user vs. maximum AP coverage range (corresponding to different P_{tx}), for a network of Wi-Fi-like secondary APs operating in TVWS under different deployment scenarios and channel widths. Results for a real example of TVWS channel availability compared to no inter-AP interference (best-case) and all APs being co-channel (worst-case); performance of Wi-Fi at 2.4 GHz also shown for reference.

represent the reference case of ignoring the effects of inter-AP interference[6], whereas the solid curves take inter-AP interference into account, as detailed in Section IV. The thin solid curves represent the worst-case scenario of all APs being co-channel (i.e. J=1, $\boldsymbol{A^j}$=$\boldsymbol{A}$). The thick solid curves characterise the performance of the Wi-Fi-like secondary network using the realistic example channel availabilities specified in Section III, whereby each AP randomly[7] selects a channel to operate on from the list of available channels obtained from the TVWS database.

Let us consider the outdoor urban scenario in Fig. 5a. When the effects of interference among APs are ignored, our results confirm the highly attractive viewpoint of a secondary Wi-Fi-like deployment in TVWS advocated by proponents of “Wi-Fi on steroids” in earlier studies. For a given power budget, operation in TVWS results in a communication range increase of 95-135% compared to IEEE 802.11g at 2.4 GHz, while achieving average downlink rates proportional to the channel width. For example, operating in TVWS with a 24 MHz channel provides a 20% higher throughput while increasing the maximum AP range by up to 240 m compared to IEEE 802.11g. In other words, this suggests that operating in TVWS would potentially yield a significantly larger downlink rate compared to traditional Wi-Fi for the same transmission distance.

However, this conclusion is seriously challenged once we consider inter-AP interference. For example, Fig. 5a shows that the range difference between traditional Wi-Fi and operating in TVWS with a 24 MHz channel reduces to at most between 67 m and 130 m, depending on the assumed TVWS availability. Moreover, the estimated downlink rate is greatly reduced due to multiple interfering APs with overlapping contention domains. This congestion effect is more pronounced for APs operating in the lower frequency range of TVWS precisely because of the accompanying larger cell sizes. Consequently, operating in TVWS with a 24 MHz channel yields a 23% *lower* throughput than traditional Wi-Fi at 2.4 GHz, despite a 20% wider channel (for P_{tx}=30 dBm). In fact, if we consider the worst-case situation of all APs being co-channel, the throughput of traditional Wi-Fi at 2.4 GHz is up to 2.4 times higher than that of the TVWS variant. Therefore, our analysis of Wi-Fi-like secondary network capacity under more realistic interference conditions clearly demonstrates that the benefits of operating in TVWS are much more moderate than what is typically claimed by the most outspoken advocates.

Considering the indoor urban scenario in Fig. 5b indicates a more favourable case for a Wi-Fi-like secondary deployment in TVWS. It is evident from Fig. 5b that, for the assumed AP density, the coverage range remains small enough that inter-AP interference does not become as dominant as for the outdoor case. This means that the range extension afforded by operating in TVWS (of up to 10-20 m, depending on

[6]This is equivalent to each AP operating on its own non-overlapping channel, such that $|\boldsymbol{A^j}|$=1 $\forall j$, $\boldsymbol{A^j_x}$=x $\forall x \in \boldsymbol{A}$; it is then straightforward to derive $\overline{R}_x$ and r_{max} analytically for a given P_{tx} and deployment scenario.

[7]Assumption of random channel allocation is apt for a distributed network.

channel width and availability) holds even under interference conditions. This confirms that one of the key potential benefits of the lower TVWS frequency band is better propagation through walls, making it attractive for indoor or indoor-to-outdoor hotspot deployments. However, the provided throughput is simply proportional to the channel bandwidth; thus in this context the TVWS spectrum itself is just providing a new ISM band with slightly extended range.

The outdoor rural scenario in Fig. 5c exhibits qualitatively similar trends to the indoor urban case. The low AP density in the rural setting leads to a lesser degradation of range and throughput from inter-AP interference compared to the outdoor urban scenario. However, in practice the performance depends on the actual TVWS availability; in the example rural area of Wipperfürth in our analysis, no 24 MHz channel chunks are available and thus the best-case scenario would be operating in TVWS using four 16 MHz channels, which more than doubles the range compared to traditional Wi-Fi but results in a 30% decrease in average throughput (for P_{tx}=30 dBm). Nonetheless, our results confirm that operating outdoor Wi-Fi hotspots in TVWS might be a technologically attractive option for rural areas due to enabling larger coverage areas for the same power budget. However, the business case for such rural use with a sparse customer base is not clear (and is beyond the scope of our paper). Thus the overall benefit of rural Wi-Fi hotspots in TVWS cannot be realistically evaluated without considering alternative technologies (e.g. what would be the efficiency and cost-structure of providing rural Internet via licensed LTE-type technology over TVWS instead).

VI. Conclusions

We have presented a quantitative analysis of the realistic potential of a Wi-Fi-like secondary network deployment in TVWS, by considering the effects of inter-AP interference and congestion and using real TVWS channel availability estimates from example urban and rural regions of Germany. We have confirmed that operating in the lower frequency TVWS band has favourable features, such as larger coverage range for the same power budget. We have shown that operating Wi-Fi hotspots in TVWS might be attractive for outdoor rural areas where user demand is low, whereas for the outdoor urban case of high user density, interference rapidly limits capacity and claims of “Wi-Fi on steroids” become less plausible. The adage of TVWS being “beach-front” spectrum holds to an extent for indoor hotspot deployments which benefit from better propagation through walls, however whether it would be preferable to instead simply regulate more ISM bands for Wi-Fi use remains an open question. Our future work will also address the issue of aggregate secondary user interference to the primary DVB-T system, which will determine the *permissible* transmit power of secondary APs, thereby likely further limiting the achievable network capacity. Therefore, the situation is much more complex than suggested by earlier studies and the associated media hype about “Wi-Fi on steroids”; a careful combined technological and quantitative economical analysis is necessary before any final judgement can be reached about the attractiveness or economical viability of large-scale Wi-Fi deployments in TVWS.

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References

[1] FCC, “Second memorandum opinion and order - in the matter of unlicensed operation in TV broadcast bands ET Docket No. 04-186 - additional spectrum for unlicensed devices below 900 MHz and in the 3 GHz band ET Docket No. 02-380.” 2010.

[2] Ofcom. (2011, Sept.) Implementing geolocation: summary of consultation responses and next steps. [Online]. Available: http://stakeholders.ofcom.org.uk/consultations/geolocation/statement/

[3] FCC. (2010) Statement of Chairman Julius Genachowski Re: Unlicenced operation in the TV broadcast bands, ET Docket No. 04-186; additional spectrum for unliscenced devices below 900 MHz and in the 3 GHz band, second memorandum opinion and order, ET Docket No. 02-380.

[4] R. Whitt. (2010, Sept.) FCC vote on white spaces lays promising foundation for Wi-Fi on steroids. Google Public Policy Blog. [Online]. Available: http://googlepublicpolicy.blogspot.com/2010/09/fcc-vote-on-white-spaces-lays-promising.html

[5] Microsoft EMEA. (2011, June) Cambridge TV white spaces consortium press release. [Online]. Available: http://www.microsoft.com/presspass/emea/presscentre/pressreleases/June2011/CambridgeTVWhiteSpacesConsortium.mspx

[6] P. Bahl *et al.*, “White space networking with Wi-Fi like connectivity,” in *Proc. ACM SIGCOMM*, Barcelona, 2009.

[7] IEEE. (2012, Jan.) Status of project P802.11af. [Online]. Available: http://www.ieee802.org/11/Reports/tgaf_update.htm

[8] S. Deb, V. Srinivasan, and R. Maheshwari, “Dynamic spectrum access in DTV whitespaces: Design rules, architecture and algorithms,” in *Proc. MobiCom*, Beijing, 2009.

[9] S. Kawade and M. Nekovee, “Can cognitive radio access to TV white space support future home networks?” in *Proc. IEEE DySPAN*, Singapore, 2010.

[10] M. Fitch *et al.*, “Wireless service provision in TV white space with cognitive radio technology: A telecom operator’s perspective and experience,” *IEEE Commun. Mag.*, vol. 49, no. 3, pp. 64 –73, March 2011.

[11] S. Kawade and M. Nekovee, “Broadband wireless delivery using an inside-out TV white space networking architecture,” in *Proc. GLOBECOM*, Houston, 2011.

[12] B. Bhaduri, E. Bright, P. Coleman, and D. L. Smith, “Landscan: Locating people is what matters,” *Geoinformatics*, vol. 5, no. 2, pp. 34 –37, 2002.

[13] K. Jones and L. Liu, “What where wi: An analysis of millions of Wi-Fi access points,” in *Proc. IEEE PORTABLE*, Orlando, 2007.

[14] A. Baddeley and R. Turner, “Spatstat: An R package for analyzing spatial point patterns,” *J. Stat. Software*, vol. 12, no. 6, pp. 1 –42, 2005.

[15] R Development Core Team, *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, 2008.

[16] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River: Prentice Hall, 2002.

[17] *IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks- Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Std. IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999), 2007.

[18] J. van de Beek, J. Riihijärvi, A. Achtzehn, and P. Mähönen, “UHF white space in Europe - a quantitative study into the potential of the 470-790 MHz band,” in *Proc. IEEE DySPAN*, Aachen, 2011.

[19] A. Achtzehn, M. Petrova, and P. Mähönen, “Deployment of a cellular network in the TVWS: A case study in a challenging environment,” in *Proc. ACM CoRoNeT*, Las Vegas, 2011.

[20] “ECO WG SE43. DRAFT ECC Report 159: Technical and operational requirements for the possible operation of cognitive radio systems in the white spaces of the frequency band 470-790 MHz,” Tech. Rep., 2011.

[21] H. Nguyen, F. Baccelli, and D. Kofman, “A stochastic geometry analysis of dense IEEE 802.11 networks,” in *Proc. INFOCOM*, Anchorage, 2007.