CO-CHANNEL COEXISTENCE OF SECONDARY OFDM NETWORKS OVER ACTIVE DTV BANDS

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by

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To my parents,

Shri. Gopal Singh Thakur

and

Smt. Sudesh Thakur

Certificate

This is to certify that the dissertation titled **Co-channel coexistence of secondary OFDM networks over active DTV bands**, submitted by **Mr. Anshul Thakur**, a Research Scholar, in the *Department of Electrical Engineering*, *Indian Institute of Technology Delhi*, *New Delhi*, *India*, for the award of the degree of **Doctor of Philosophy**, is a record of an original research work carried out by him under my supervision and guidance. The dissertation fulfills all requirements as per the regulations of this Institute and in my opinion has reached the standard needed for submission. Neither this dissertation nor any part of it has been submitted for any degree or academic award elsewhere.

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Abstract

With the advent of fifth generation and beyond (5G+ and 6G) networks and Internet of Things (IoT) communications, the demand for increased wireless connectivity has increased many-fold. Realizing that allocating more from the finite available spectrum can only serve as a temporary fix, regulatory bodies and the research community have started to explore increasing the spectral efficiency of the already allocated frequency bands. At the same time, developing technologies that also overcome the poor economies of scale associated with deployments in sparsely populated rural areas is essential to provide ubiquitous access.

The lower end of the UHF band is particularly attractive for such technologies owing to its excellent propagation and penetration characteristics. This enables wider coverage while requiring smaller amounts of infrastructure. So far, the UHF bands have primarily been used by television (TV) and radio services. Regulatory bodies worldwide are rapidly realizing the need to open up this part of the spectrum for opportunistic access by secondary networks.

Any opportunistic use of any actively used spectrum band risks disrupting the incumbent network's operation by causing excessive signal interference. Owing to this, standards like IEEE 802.11af, IEEE 802.22 Wireless Regional Area Network (WRAN) and Long-Term Evolution in Unlicensed Spectrum (LTE-U) have been developed to steer clear of the regions referred to as TV Black Spaces (TVBS) and TV Gray Spaces (TVGS) where an incumbent is transmitting, and claim the TV White Spaces (TVWS) that are found to exist in the TV bands. As a DTV network coverages span tens of kilometers, such interference avoidance based deployment renders a huge geographical region unserviceable by the secondary networks. However, an interference management based intelligent and agile secondary network that can operate within the varying interference margins within the TVBS would be able to overcome this lacuna.

Motivated by the above observations, this dissertation explores the problem of deploying such an interference managing secondary network in the TVBS and TVGS areas. The first part of the dissertation lays the groundwork for deploying secondary networks in co-channel modes with an ongoing DTV broadcast by validating the technical feasibility of the approach. To this end, the interference caused by a secondary orthogonal frequency division multiplexing (OFDM) network on the reception of the DTV broadcast at a DTV receiver is analytically quantified and verified experimentally. A framework is then pro-

posed to manage the interference caused by secondary transmission at a DTV receiver by varying the amount of its temporal and spectral overlap with the DTV signal.

Owing to the unidirectional nature of DTV broadcast, the biggest challenge of utilizing an active TV channel is to detect the presence of active DTV receivers, which act as hidden nodes. While some new standards, such as ATSC 3.0, are evolving to cater to an interactive TV experience requirement by making optional provisions for feedback via an OTA channel, it will take time before the technology gains widespread adoption. For regions that continue to work with the legacy DTV network, the second part of the dissertation explores a method to work around the issue of hidden nodes with minimal or no changes in the existing DTV networks. As no direct feedback method from the DTV receivers is available, the problem is broken into two steps: estimating the locations of active DTV receivers and finding the signal conditions and interference impact at those DTV receivers.

Finally, the paradigm of the next-generation ATSC 3.0 DTV network where feedback could be made available is considered in the third part of the dissertation. While the problems of localization and obtaining the interference state still remain the same, the availability of some feedback on the Dedicated Return Channel (DRC) of the ATSC 3.0 network allows the use of novel techniques to maximize the coexistence opportunity. Thus, a method to harness the feedback signals from the DTV receivers for localization is proposed. With the DTV receivers now unhidden, an online learning algorithm is proposed for managing the interference at the DTV receivers. This enables the co-channel coexistence of the secondary networks with an active DTV broadcast in a ubiquitous manner.

सारांश

पांचवीं पीढ़ी और उससे आगे (5G+ और 6G) नेटवर्क और इंटरनेट ऑफ थिंग्स (IoT)संचार के आगमन के साथ, बढ़ी हुई वायरलेस कनेक्टिविटी की मांग कई गुना बढ़ गई है। यह महसूस करते हुए कि परिमित उपलब्ध स्पेक्ट्रम से अधिक आवंटन केवल एक अस्थायी सुधार के रूप में काम कर सकता है, नियामक निकायों और अनुसंधान समुदाय ने पहले से आवंटित आवृत्ति बैंड की वर्णक्रमीय दक्षता बढ़ाने का पता लगाना शुरू कर दिया है। साथ ही, विकासशील प्रौद्योगिकियां जो कम आबादी वाले ग्रामीण इलाकों में तैनाती से जुड़े पैमाने की गरीब अर्थव्यवस्थाओं को दूर करती हैं, सर्वव्यापी पहुंच प्रदान करने के लिए आवश्यक हैं।

यूएचएफ (UHF) बैंड का निचला हिस्सा अपने उत्कृष्ट प्रसार और पैठ विशेषताओं के कारण ऐसी तकनीकों के लिए विशेष रूप से आकर्षक है। यह कम मात्रा में बुनियादी ढांचे की आवश्यकता होने पर व्यापक कवरेज को सक्षम बनाता है। अब तक, यूएचएफ बैंड का मुख्य रूप से टेलीविजन (टीवी) और रेडियो सेवाओं द्वारा उपयोग किया जाता रहा है। दुनिया भर में नियामक निकाय माध्यमिक नेटवर्क द्वारा अवसरवादी पहुंच के लिए स्पेक्ट्रम के इस हिस्से को खोलने की आवश्यकता को तेजी से महसूस कर रहे हैं।

किसी भी सक्रिय रूप से उपयोग किए जाने वाले स्पेक्ट्रम बैंड के किसी भी अवसरवादी उपयोग से अत्यधिक सिग्नल हस्तक्षेप के कारण मौजूदा नेटवर्क के संचालन को बाधित करने का जोखिम होता है। इसके कारण, IEEE 802.11af, IEEE 802.22वायरलेस रीजनल एरिया नेटवर्क (WRAN) और बिना लाइसेंस वाले स्पेक्ट्रम (LTE-U) में लॉन्ग-टर्म इवोल्यूशन जैसे मानकों को टीवी ब्लैक स्पेस (TVBS) के रूप में संदर्भित क्षेत्रों से दूर रखने के लिए विकसित किया गया है। और टीवी ग्रे स्पेस (टीवीजीएस) जहां एक पदाधिकारी प्रसारण कर रहा है, और टीवी बैंड में मौजूद टीवी व्हाइट स्पेस (टीवीडब्लूएस) का दावा करता है। एक डीटीवी नेटवर्क कवरेज के रूप में दसों किलोमीटर तक फैला हुआ है, इस तरह के हस्तक्षेप से बचाव आधारित तैनाती एक विशाल भौगोलिक क्षेत्र को द्वितीयक नेटवर्क द्वारा अनुपयोगी बना देती है। हालांकि, एक हस्तक्षेप प्रबंधन आधारित बुद्धिमान और चुस्त माध्यमिक नेटवर्क जो टीवीबीएस के भीतर अलग-अलग हस्तक्षेप मार्जिन के भीतर काम कर सकता है, इस कमी को दूर करने में सक्षम होगा।

उपरोक्त टिप्पणियों से प्रेरित होकर, यह शोध प्रबंध टीवीबीएस और टीवीजीएस क्षेत्रों में इस तरह के एक हस्तक्षेप प्रबंधन माध्यमिक नेटवर्क को तैनात करने की समस्या की पड़ताल करता है। शोध प्रबंध का पहला भाग दृष्टिकोण की तकनीकी व्यवहार्यता को मान्य करके चल रहे डीटीवी प्रसारण के साथ सह-चैनल मोड में माध्यमिक नेटवर्क को तैनात करने के लिए आधारभूत कार्य करता है। इसके लिए, डीटीवी रिसीवर पर डीटीवी प्रसारण के रिसेप्शन पर द्वितीयक ऑर्थोगोनल फ्रीक्वेंसी डिवीजन मल्टीप्लेक्सिंग (ओएफडीएम) नेटवर्क के कारण होने वाले व्यवधान को विश्लेषणात्मक रूप से परिमाणित और प्रयोगात्मक रूप से सत्यापित किया जाता है। डीटीवी सिग्नल के साथ अपने अस्थायी और वर्णक्रमीय ओवरलैप की मात्रा को अलग-अलग करके डीटीवी रिसीवर पर द्वितीयक संचरण के कारण हस्तक्षेप का प्रबंधन करने के लिए एक ढांचा प्रस्तावित किया गया है।

डीटीवी प्रसारण की यूनिडायरेक्शनल प्रकृति के कारण, सक्रिय टीवी चैनल का उपयोग करने की सबसे बड़ी चुनौती सक्रिय डीटीवी रिसीवर की उपस्थिति का पता लगाना है, जो छिपे हुए नोड्स के रूप में कार्य करते हैं। जबकि कुछ नए मानक, जैसे एटीएससी 3.0 (ATSC 3.0), एक ओटीए(OTA) चैनल के माध्यम से प्रतिक्रिया के लिए वैकल्पिक प्रावधान करके एक इंटरैक्टिव टीवी अनुभव की आवश्यकता को पूरा करने के लिए विकसित हो रहे हैं, तकनीक को व्यापक रूप से अपनाने से पहले इसमें समय लगेगा। उन क्षेत्रों के लिए जो लीगेसी डीटीवी नेटवर्क के साथ काम करना जारी रखते हैं, निबंध का दूसरा भाग मौजूदा डीटीवी नेटवर्क में न्यूनतम या कोई बदलाव के साथ छिपे हुए नोड्स के मुद्दे के आसपास काम करने की विधि की खोज करता है। चूंकि डीटीवी रिसीवर से कोई प्रत्यक्ष प्रतिक्रिया पद्धति उपलब्ध नहीं है, समस्या दो चरणों में विभाजित है: सक्रिय डीटीवी रिसीवर के स्थानों का अनुमान लगाना और उन डीटीवी रिसीवर पर सिग्नल की स्थिति और हस्तक्षेप प्रभाव का पता लगाना।

अंत में, अगली पीढ़ी के एटीएससी 3.0 डीटीवी नेटवर्क का प्रतिमान जहां फीडबैक उपलब्ध कराया जा सकता है, शोध प्रबंध के तीसरे भाग में माना जाता है। जबकि स्थानीयकरण और हस्तक्षेप की स्थिति प्राप्त करने की समस्याएं अभी भी समान हैं, एटीएससी 3.0 नेटवर्क के समर्पित रिटर्न चैनल (DRC) पर कुछ प्रतिक्रिया की उपलब्धता सह-अस्तित्व के अवसर को अधिकतम करने के लिए उपन्यास तकनीकों के उपयोग की अनुमति देती है। इस प्रकार, स्थानीयकरण के लिए डीटीवी रिसीवर से प्रतिक्रिया संकेतों का उपयोग करने का एक तरीका प्रस्तावित है। डीटीवी रिसीवर अब अछूते हैं, डीटीवी रिसीवर्स में हस्तक्षेप के प्रबंधन के लिए एक ऑनलाइन लर्निंग एल्गोरिदम प्रस्तावित है। यह माध्यमिक नेटवर्क के सह-चैनल सह-अस्तित्व को एक सक्रिय डीटीवी प्रसारण के साथ सर्वव्यापी तरीके से सक्षम बनाता है।

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List of Acronyms

ATSC	Advanced Television Systems Committee
AWGN	Additive White Gaussian Noise
BAT	Broadcast Access Terminal
BS	Base Station
BTS	Broadcast Terminal Station
CR	Cognitive Radio
CSI	Channel State Information
DTV	Digital Television
DVB-T	Digital Video Broadcasting - Terrestrial
DVB-T2	Digital Video Broadcasting - Second Generation Terrestrial
eNB	evolved Node B
FFT	Fast Fourier Transform
IoT	Internet-of-Things
LTE	Long-Term Evolution
OFDM	Orthogonal Frequency Division Multiplexing
OTA	Over The Air
QoS	Quality of Service
RF	Radio Frequency
RL	Reinforcement Learning
RMSE	Root Mean Square Error
SC-FDMA	Single Carrier Frequency Division Multiple Access
SNR	Signal-to-Noise-Ratio
SINR	Signal to Interference and Noise Ratio
TA	Timing Advance
TVBS	Television Black Space
TVGS	Television Grey Space
TVWS	Television White Space

List of Symbols

$\text{Tx}^{(\text{D})}$	DTV Transmitter
$\text{Rx}^{(D)}$	DTV receiver
$\text{Rx}^{(S)}$	Secondary uplink receiver BS
$\text{Tx}^{(S)}$	Secondary uplink transmitter
$s^{(D)}(t)$	Transmitted DTV signal
$r^{(D)}(t)$	Received DTV signal at the DTV receiver
$r^{(S)}(t)$	Received secondary signal at the DTV receiver
$T^{(D)}$	Total symbol duration of DTV signal
$T^{(S)}$	Total symbol duration of secondary signal
$T_u^{(D)}$	Useful symbol duration of DTV signal
$T_u^{(S)}$	Useful symbol duration of secondary signal
$T_g^{(D)}$	Guard interval in DTV signal
$T_g^{(S)}$	Guard interval in secondary signal
$N^{(D)}$	Total subcarriers in DTV signal
$N^{(S)}$	Active subcarriers in secondary signal
$N_{\max}^{(S)}$	Maximum subcarriers in secondary signal
$P_t^{(D)}$	Power transmitted by the DTV transmitter
$P_t^{(S)}$	Power transmitted by the secondary transmitter
$P_r^{(D)}$	DTV signal power received by the DTV receiver
$\hat{P}_r^{(D)}$	Estimated DTV signal power received by the DTV receiver
$P_r^{(S)}$	Secondary signal power received by the DTV receiver
$'$	Number of symbol slots occupied by secondary in $T^{(D)}$
$'_{\max}$	Maximum number of secondary symbol slots in $T^{(D)}$

$\eta^{(D)}$	Path loss exponent for DTV signal
$\eta^{(S)}$	Path loss exponent for secondary signal
$\Gamma^{(D)}$	Average SINR experienced at the DTV receiver
$\Gamma_{th}^{(D)}$	Average SINR threshold at the DTV receiver
$\Gamma_{th}^{(S)}$	Average SINR experienced at the secondary receiver
Γ^{R}	SNR achieved for the selected MCS $R^{(S)}$
$\Gamma_{\min}^{R}$	Minimum SNR required for the selected MCS $R^{(S)}$
ξ'	Number of multipath components for DTV signal
ξ	Number of multipath components for secondary signal
l'	Index of DTV signal's symbol block
l	Index of secondary signal's symbol block
$\tau_{n'}$	Signal delay in the n'th multipath of DTV signal
τ_{n}	Signal delay in the nth multipath of secondary signal
t_{off}	Random delay between the arrival of a DTV symbol and its first interfering secondary signal ($l' = 0$)
$\Phi_{p'}$	OFDM basis function for the p'th DTV subcarrier
$I_{p'}$	Interference on the p'th DTV subcarrier due to secondary co-channel transmission
$\mathbb{R}^{(S)}$	Set of MCS supported by the secondary system
$R^{(S)}$	MCS from $\mathbb{R}^{(S)}$ by the secondary transmitter
d_A	DTV transmitter to secondary transmitter distance
d_B	DTV transmitter to secondary receiver distance
d_{AB}	Secondary transmitter to secondary receiver distance
d_{AD}	Secondary transmitter to nearest DTV receiver distance
d_{c}	Minimum separation between secondary transmitter and DTV receiver to avoid excess interference
$\mathbb{A}$	Total DTV coverage area
c	Secondary coverage area inside $\mathbb{A}$
M	Number of secondary nodes in the region c
U	Number of active DTV receiver nodes in the region c
$\lambda^{(S)}$	Secondary node distribution density in region c
$\lambda^{(D)}$	Active DTV receivers distribution density in region c
$O(c)$	OTA TV Ownership rate in area c
$p_{act}(t)$	Cumulative channel rating at time t

$\Delta f^{(S)}$	Frequency offset between DTV and secondary signals
$\mathbf{x}_i^{(S)}$	Coordinates of secondary nodes
$\mathbf{x}_j^{(D)}$	Coordinates of DTV nodes
d_{cor}	Decorrelation distance of the shadowing process
d_i	Distance of ith secondary node from DTV transmitter
χ	Average DTV power to interference power ratio experienced at the DTV receiver
χ_{th}	Threshold DTV power to interference power ratio experienced at the DTV receiver
$p_{out}^{(D)}$	Outage probability in the DTV network
$p_{out,th}^{(D)}$	Threshold outage probability in the DTV network
$p_{out}^{(S)}$	Outage probability in the secondary link
$p_{out,th}^{(S)}$	Threshold outage probability in the secondary link
σ_D	Shadowing coefficient for the DTV signal
$\Psi^{(D)}$	Log-Normal shadowing process for the DTV signal
$H_l^{(D)}$	Channel gain on the lth DTV subcarrier
I_l	Interference gain on the lth DTV subcarrier due to secondary co-channel transmission
$H^{(D)}$	Channel gain in the DTV signal
$I^{(S)}$	Interference gain caused at the DTV receiver due to secondary node transmission
γ	Analytical semivariogram of DTV signals sampled spatially
$\hat{\gamma}$	Empirical sermivariogram of DTV signals sampled spatially
δ_{DD}	Path delay between the DTV transmitter and DTV receiver
δ_{DS}	Path delay between the DTV transmitter and secondary BS
δ_{SD}	Path delay between the secondary BS and DTV receiver
ϵ	Systematic error introduced in time advance commands due to discretization
$\mathbf{K}$	Set of secondary transmission parameters based on number of occupied time slots and subcarrier frequencies

$\mathcal{U}$	Action space of secondary transmitter
u_n	Action taken in time slot n
$X_n^{(D)}$	Outage state of DTV receiver in time slot n
μ	Policy vector adopted by the secondary transmitter
β	Learning rate in RL algorithm
α_n	Probabilty of choosing exploratory action in time slot n