ENABLING WIRELESS BROADBAND VIA COGNITIVE RADIO NETWORKS

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by

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Certificate

This is to certify that the dissertation entitled **Enabling Wireless Broadband via Cognitive Radio Networks**, submitted by **Mr. Satyam Agarwal**, a Research Scholar, in the *Department of Electrical Engineering*, *Indian Institute of Technology 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

Demand for wireless broadband has increased tremendously over the past few years. Due to the spectrum scarcity problem in the licensed bands, cognitive radio (CR) could be employed to provide broadband services to the users. In this dissertation, the issues of efficient broadband coverage involving CR network (CRN) in urban and rural areas are addressed. In rural areas, a significant fraction of the population is deprived of broadband access due to the problem of connectivity. The unique challenges in enabling rural connectivity are sparsity of population locations and modest income of the villagers, which induce low return on investment to the conventional cellular network providers. Due to scarcity of spectrum resource, communication over unused TV bands, called white space access (WSA), is being considered as a possible solution. In the first part of this dissertation, to provide mid-haul connectivity to rural users, a novel cluster-based WSA network architecture and the associated protocols are proposed for efficient rural broadband coverage. Via analytical study, the proposed architecture is demonstrated to be cost-effective and energy-efficient, while being scalable at the same time.

In the urban scenario, cellular and other dynamic spectrum bands in GHz range are exploited for CR operation. Here, the primary user (PU) activity is more agile, and CRs need to sense the channel intermittently for dynamic spectrum access (DSA). In energy-constrained CRNs, the choice on single-channel access (SCA) versus multichannel access (MCA) is critical for energy saving and sustainable network operation for DSA. In the second part of this dissertation, energy efficiency of switched MCA and fixed SCA is studied and compared in CRNs. In MCA, a secondary user (SU) switches channel with certain probability whenever it encounters a busy channel. In SCA on the other hand, the SU stays on the same channel for its usage and waits for its availability. Via an analytical framework the channel utilization and energy efficiency is derived for the two schemes. From the results PU traffic dependent optimum switching probability is examined in MCA and the regime of PU activity dynamics where SCA outperforms MCA is investigated.

In the third part of this dissertation, a class of energy-efficient single-channel DSA (SC-DSA) protocols is proposed for SU communication over one PU channel. The proposed variants of SC-DSA can be optimized with respect to different back-off strategies and SU packet lengths. Via Markov chain models and numerical analysis, the optimal SU packet length and inter-sensing time are derived for optimal SU performance in the

SC-DSA variants. The protocol performance is evaluated in terms of SU goodput, SU energy efficiency, and PU collision ratio. Adaptability of the proposed SU operation protocol in practical scenarios is tested over cellular GSM band as well as over ISM band carrying real-time video over IP based PU traffic. Performance studies demonstrate that the proposed protocols offer significantly high channel utilization while keeping the PU collisions below an acceptable threshold. An outline of the proposed protocol operation, wherein the protocol adapts to the changing PU traffic load for optimized spectrum access performance, is also given.

Finally, to enhance the last-mile CR solution in urban/sub-urban/rural areas, in the last part of the dissertation, a new paradigm called cognitive multihoming (CM) is introduced, which alleviates the spectrum scarcity problem in the cellular networks. In CM, a CR-enabled base station transmits to the users simultaneously over the licensed cellular bands and PU bands in CRNs. The CR aspect incurs lower transmission cost, however at the expense of higher energy consumption due to intermittent channel sensing. On the other hand, transmission via licensed cellular network (LCN) is expensive because of its licensing premium. Performance of the proposed CM is analyzed in two scenarios. In the first scenario multiple real-time (RT) and non-RT users request unicast downlink content from the network, while in the second scenario multiple CM users request scalable video content from the network. To minimize the transmission cost while meeting the users' energy and received video quality constraints, sensing duration and transmission rate over CRN, transmission rate over LCN, and network selection for retransmission of lost packets are adjusted. Optimal resource allocation and call admission control algorithm is proposed for the two scenarios. The proposed scheme is compared with the cases where a user operates over a single network, either LCN or CRN. The system performance results indicate that the proposed CM strategy significantly decreases the cost to the users as well as serves a higher number of users.

The solutions proposed in this dissertation aid in capacity enhancement of the present bandwidth-constrained wireless networks as well as offer energy-efficient network performance. Via extensive analytical formulations, deeper insights into the protocol operation in CRNs have been developed which would be useful in wide application areas, such as, rural broadband access, cellular broadband networks, and CR sensor networks.

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List of Acronyms

AP	Access Point
ACK	Acknowledgment
BS	Base Station
CH	Cluster Head
CPE	Customer Premise Equipment
CR	Cognitive Radio
CRN	Cognitive Radio Network
CCP	Convex Concave Procedure
CTS	Clear to Send
CCC	Common Control Channel
CRSN	Cognitive Radio Sensor Networks
CMT	Concurrent Multipath Transfer
CM	Cognitive Multihoming
CSMA	Carrier Sense Multiple Access
DTMC	Discrete Time Markov Chain
DSA	Dynamic Spectrum Access
DC	Difference of Convex
DBF	Distributed Beamforming
eDSA	Energy-efficient Dynamic Spectrum Access
FCC	Federal Communications Commission
FEC	Forward Error Correction
GOP	Group of Pictures
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced

LTE-U	Long Term Evolution-Unlicensed
LSA	Licensed Shared Access
LOS	Line of Sight
LCN	Licensed Cellular Network
LWA	LTE WiFi Aggregation
MAC	Medium Access Control
MCA	Multichannel Access
sMCA	Simplified Multichannel Access
pMCA	Probabilistic Multichannel Access
PU	Primary User
PoP	Point of Presence
QoS	Quality of Service
RTS	Request to Send
RBA	Rural Broadband Access
RAT	Radio Access Technology
RT	Real-time
RB	Resource Block
SC	Single Channel
SCA	Single Channel Access
SNA	Single Network Access
SU	Secondary User
SP	Service Provider
SNR	Signal to Noise Ratio
SVC	Scalable Video Coding
TDMA	Time Division Multiple Access
TVWS	TV White Space
UHF	Ultra High Frequency
VHF	Very High Frequency
WSA	White Space Access

List of Symbols

α	Packet arrival probability
σ_r^2	Variance of the Rayleigh fading component
γ	Signal to noise ratio
ε	Path loss exponent
π	Steady state probability of a DTMC
ϕ, Φ	Energy consumption
μ	PU channel ‘ON’ duration mean
λ	PU channel ‘OFF’ duration mean
η	PU collision ratio threshold
χ	User cost preference
φ	Frame error probability
ζ	Channel sensing duration
B	Channel bandwidth
$\mathcal{C}$	User cost
d, u	Data (bits)
$\mathcal{E}$	Energy efficiency
$\mathbb{E}[\cdot]$	Expectation
f_D	Doppler frequency
F	Fading margin
G, H	Probability density function
$\mathcal{G}$	SU goodput
h	Rayleigh fading component
H_l	Header length
$\mathscr{L}$	Lagrange function

N_u	Number of users
N_e	Number of CPEs in the network
N_c	Number of clusters in the network
N_d	Number of data channels
N_v	Number of villages
N_{ch}	Number of PU channels
$\mathbf{P}, \mathbf{Q}$	One-step state transition probability of a DTMC
$Pr(\cdot)$	Probability
p_{fa}	Probability of false alarm
p_{md}	Probability of mis-detection
P_{out}	Outage probability
P_{suc}	Data packet transmission success
P_t	Transmitter power
P_r	Receiver power
$\mathcal{Q}$	Video quality metric
r	distance
R	Transmission rate
$\mathcal{R}_c$	PU collision ratio
T	Slot duration
$\mathcal{T}$	Throughput
$\mathscr{U}$	User utility
$\mathcal{U}$	Utilization