

ENERGY-EFFICIENT DATA TRANSMISSION STRATEGIES OVER TEMPORALLY-CORRELATED WIRELESS CHANNELS

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ENERGY-EFFICIENT DATA TRANSMISSION STRATEGIES OVER TEMPORALLY-CORRELATED WIRELESS CHANNELS

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**To my parents,
Shri. Pradip Kumar Mukherjee
and
Smt. Dipanwita Mukherjee**

Certificate

This is to certify that the dissertation entitled **Energy-Efficient Data Transmission Strategies over Temporally-Correlated Wireless Channels**, submitted by **Mr. Priyadarshi Mukherjee**, 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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Priyadarshi Mukherjee

Abstract

A dramatic rise in global Internet traffic has been observed in the last decade. To cope up with this increasing trend of mobile data traffic as well as the rapid growth in the number of communication devices, both academia as well as industry are trying to find a ‘green’ solution to the problem. Future wireless communication systems such as fifth-generation (5G) networks are being designed accordingly, to jointly address the aspect of energy efficiency and spectral efficiency. The future wireless networks involve applications like Internet of Things (IoT) and wireless sensor networks (WSN), which generally operate in energy-constrained scenarios and hence, they require judicious use of energy. It is not wise for these battery-limited applications to perform data transmission when the channel is unusable to do so but when it is good enough to support a minimum data rate. Thus it can be observed that current state of the fading wireless channel plays a crucial role in this context. As a result, this dissertation aims at the simultaneous enhancement of both spectral and energy efficiency of the wireless communication systems.

To this end, the first part of dissertation introduces a novel theoretical framework for characterizing the temporally varying wireless channel. The analytical model is validated through extensive simulation. The proposed model is then extended to define two performance metrics, namely short term outage probability and short term channel capacity, which effectively capture short-term temporal variations of the channel. An application dependent upper bound is also proposed on the time interval over which the proposed characterization holds. Further, a non-trivial trade-off that exists between the upper bound and quality of characterization is also accurately investigated.

The proposed channel characterization helps us estimate the amount of data transfer possible in next few slots without requiring the channel state information (CSI) in those slots. But this characterization does not comment on the actual CSI in those slots. On the contrary, link-layer communication is based on the actual CSI in a particular time slot. Hence a novel channel-aware retransmission technique, namely D-SW, is proposed in the next chapter, that reduces chances of unnecessary probing of the channel. Simulation results illustrate that D-SW results in significant increase in both data throughput and energy efficiency over the existing approaches.

D-SW reduces unnecessary channel probing, but only when the channel is unusable for data transmission. It does not do the same irrespective of channel condition. As a result, a more generalized link-layer communication strategy cDIP is proposed in the

next chapter. cDIP reduces unnecessary probing of the channel irrespective of its current condition. This proposed strategy essentially estimates both the waiting interval when the channel is unusable for data transmission and the continuous transmission interval otherwise, thus overcoming the disadvantage of D-SW. In this way cDIP avoids the use of regular feedback packets, which leads to its enhanced performance in terms of obtaining higher data throughput as well as energy efficiency.

We observe that even though cDIP is channel-aware in estimating the waiting and transmission intervals, it is not able to capitalize on the CSI to the fullest. Hence we propose another channel-aware link-layer transmission strategy DF-AMC. DF-AMC, like the conventional adaptive modulation and coding (AMC) scheme, partitions the whole CSI range into intervals where each interval corresponds to a particular modulation scheme. However, novelty lies in the fact that DF-AMC estimates the duration over which channel state will continue to remain in a particular interval when it currently belongs to that interval. This not only greatly reduces the frequency of feedback packets like cDIP, but it also allows the transmitter to make the most use of the channel by modulation scheme variation.

DF-AMC is a communication strategy which can have a variety of applications. In the last part, we investigate the application of the analytical framework proposed in DF-AMC in a multichannel energy harvesting cognitive radio scenario. Here a protocol is proposed that optimally decides when to transmit or harvest and also for how long. We further claim that unlike the existing works, both the channel state and the primary user characteristics need to be considered for decision making.

सार

पिछले एक दशक में वैश्विक इंटरनेट यातायात में नाटकीय वृद्धि देखी गई है। मोबाइल डेटा ट्रैफ़िक के इस बढ़ते चलन के साथ-साथ संचार उपकरणों की संख्या में तेज़ी से वृद्धि करने के लिए, दोनों शिक्षाविदों के साथ-साथ उद्योग भी समस्या का 'हरित' समाधान खोजने की कोशिश कर रहे हैं। पांचवीं पीढ़ी (5G) नेटवर्क जैसे भविष्य के वायरलेस संचार प्रणालियों को ऊर्जा दक्षता और वर्णक्रमीय दक्षता के पहलू को संयुक्त रूप से संबोधित करने के लिए डिज़ाइन किया गया है। भविष्य के वायरलेस नेटवर्क में इंटरनेट ऑफ थिंग्स (IoT) और वायरलेस सेंसर नेटवर्क (WSN) जैसे एप्लिकेशन शामिल होते हैं, जो आमतौर पर ऊर्जा-बाधित परिदृश्यों में काम करते हैं और इसलिए, उन्हें ऊर्जा के विवेकपूर्ण उपयोग की आवश्यकता होती है। इन बैटरी-सीमित अनुप्रयोगों के लिए डेटा संचरण करना बुद्धिमानी नहीं है जब चैनल ऐसा करने के लिए अनुपयोगी हो लेकिन जब यह न्यूनतम डेटा दर का समर्थन करने के लिए पर्याप्त हो। इस प्रकार यह देखा जा सकता है कि लुप्त होती वायरलेस चैनल की वर्तमान स्थिति इस संदर्भ में महत्वपूर्ण भूमिका निभाती है। नतीजतन, इस शोध प्रबंध का उद्देश्य वायरलेस संचार प्रणालियों की वर्णक्रमीय और ऊर्जा दक्षता दोनों को एक साथ बढ़ाना है।

यह अंत करने के लिए, शोध प्रबंध का पहला हिस्सा अस्थायी रूप से भिन्न वायरलेस चैनल को चिह्नित करने के लिए एक उपन्यास सैद्धांतिक रूपरेखा पेश करता है। विश्लेषणात्मक मॉडल व्यापक सिमुलेशन के माध्यम से मान्य है। प्रस्तावित मॉडल को तब दो प्रदर्शन मैट्रिक्स, अर्थात् अल्पकालिक आउटेज संभावना और अल्पावधि चैनल क्षमता को परिभाषित करने के लिए बढ़ाया जाता है, जो प्रभावी रूप से चैनल के अल्पकालिक लौकिक विविधताओं को पकड़ते हैं। ऊपरी अंतराल पर एक अनुप्रयोग निर्भर ऊपरी सीमा भी प्रस्तावित है जिस पर प्रस्तावित लक्षण वर्णन है। इसके अलावा, एक गैर-तुच्छ व्यापार-बंद जो चरित्र की ऊपरी सीमा और गुणवत्ता के बीच मौजूद है, की भी सटीक जांच की जाती है।

प्रस्तावित चैनल लक्षण वर्णन हमें उन स्लॉट्स में चैनल स्टेट की जानकारी (CSI) की आवश्यकता के बिना अगले कुछ स्लॉट्स में डेटा ट्रांसफर की मात्रा का अनुमान लगाने में मदद करता है। लेकिन यह लक्षण वर्णन उन स्लॉट्स में वास्तविक सीएसआई पर टिप्पणी नहीं करता है। इसके विपरीत, लिंक-परत संचार एक विशेष समय स्लॉट में वास्तविक सीएसआई पर आधारित है। इसलिए अगले चैप्टर में एक उपन्यास चैनल-जागरूक रिट्रांसमिशन तकनीक, अगले अध्याय में प्रस्तावित है, जो चैनल की अनावश्यक जांच की संभावना को कम करता है। सिमुलेशन के परिणाम बताते हैं कि डी-एसडब्ल्यू का परिणाम मौजूदा दृष्टिकोण से अधिक डेटा ध्रुपट और ऊर्जा दक्षता दोनों में उल्लेखनीय वृद्धि है।

D-SW अनावश्यक चैनल जांच को कम करता है, लेकिन केवल जब चैनल डेटा ट्रांसमिशन के लिए अनुपयोगी होता है। यह चैनल की स्थिति के बावजूद ऐसा नहीं करता है। परिणामस्वरूप, अगले अध्याय में एक अधिक सामान्यीकृत लिंक-लेयर संचार रणनीति cDIP प्रस्तावित है। cDIP चैनल की अनावश्यक जांच को कम करता है, चाहे उसकी वर्तमान स्थिति कुछ भी हो। यह प्रस्तावित रणनीति अनिवार्य रूप से प्रतीक्षा अंतराल दोनों का अनुमान लगाती है जब चैनल डेटा ट्रांसमिशन के लिए अनुपयोगी होता है और निरंतर प्रसारण अंतराल अन्यथा, इस प्रकार डी-एसडब्ल्यू के नुकसान पर काबू पाने। इस तरह cDIP नियमित फीडबैक पैकेट के

उपयोग से बचता है, जो उच्च दक्षता थ्रूपुट के साथ-साथ ऊर्जा दक्षता प्राप्त करने के मामले में अपने उन्नत प्रदर्शन की ओर जाता है।

हम देखते हैं कि प्रतीक्षा और प्रसारण अंतराल के आकलन में भले ही cDIP चैनल-जागरूक हो, लेकिन यह CSI को पूर्ण रूप से भुनाने में सक्षम नहीं है। इसलिए हम एक और चैनल-जागरूक लिंक-लेयर ट्रांसमिशन रणनीति DF-AMC का प्रस्ताव करते हैं। DF-AMC, पारंपरिक अनुकूली मॉड्यूलेशन और कोडिंग (AMC) योजना की तरह, पूरे CSI को अंतराल में विभाजित करता है जहां प्रत्येक अंतराल एक विशेष मॉड्यूलन योजना से मेल खाती है। हालांकि, नवीनता इस तथ्य में निहित है कि डीएफ-एएमसी उस अवधि का अनुमान लगाता है जिस पर चैनल राज्य एक विशेष अंतराल में बना रहेगा, जब वह वर्तमान में उस अंतराल से संबंधित होगा। यह न केवल cDIP जैसे फीडबैक पैकेट्स की आवृत्ति को बहुत कम करता है, बल्कि यह ट्रांसमीटर को मॉड्यूलेशन स्कीम वेरिएशन द्वारा चैनल का अधिकतम उपयोग करने की अनुमति देता है।

DF-AMC एक संचार रणनीति है जिसमें विभिन्न प्रकार के अनुप्रयोग हो सकते हैं। पिछले भाग में, हम एक मल्टीचैनल एनर्जी हार्वेस्टिंग कॉग्निशन रेडियो परिदृश्य में DF-AMC में प्रस्तावित विश्लेषणात्मक ढांचे के आवेदन की जांच करते हैं। यहां एक प्रोटोकॉल प्रस्तावित किया गया है, जो कब और कैसे या कब तक प्रसारित करना है, यह तय करता है। हम आगे दावा करते हैं कि मौजूदा कार्यों के विपरीत, चैनल राज्य और प्राथमिक उपयोगकर्ता विशेषताओं दोनों को निर्णय लेने के लिए विचार करने की आवश्यकता है।

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List of Symbols

T_p	Slot duration
f_D	Maximum Doppler frequency
v	Node velocity
f_c	Carrier frequency
c	Velocity of light in vacuum
y	Received signal
P	Transmission power
$h(t)$	Complex channel gain at time t
a	Transmitted signal
n	Noise signal with zero mean and variance σ_0^2
$h_I(t), h_Q(t)$	In-phase and quadrature components of $h(t)$
N_p	Number of propagation paths
$\alpha_n(\phi_n)$	Angle of arrival (initial phase) of n^{th} propagation path
K	Rice factor
$X(Z)$	Received signal envelope (power)
$\mathbb{E}$	Expectation operator
$I_0(\cdot)$	Zero-order modified Bessel function of the first kind
$X_{th}(Z_{th})$	Target $X(Z)$ threshold
$\dot{X}(\dot{Z})$	Time derivative of $X(Z)$
$\Phi_1(\cdot)$	CDF of standard univariate normal distribution
$\Psi(\Omega)$	Temporal variation of $X(Z)$ over next ζ slots
$\bar{P}_{\text{out}}$	Conventional outage probability
$P_{\text{out}}^{(\text{ST})}(Z(t), \zeta)$	Short-term outage probability

$Q(\cdot)$	CCDF of standard univariate normal distribution
$\bar{C}$	Conventional channel capacity
$C^{(\text{ST})}(Z(t), \zeta)$	Short-term channel capacity
$\Gamma(\cdot, \cdot)$	Upper incomplete Gamma function
P	Pilot signal power
T_{pr}	Pilot and feedback signal duration
$\Lambda_{\text{prop}}(Z(t), \zeta)$	Achievable throughput for next ζ slots
$\eta^{(\zeta)}(Z(t), \zeta)$	Energy efficiency over next ζ slots
ρ	Correlation co-efficient
$J_0(\cdot)$	Bessel function of first kind and of zeroth order
$\rho^{(l)}$	Acceptable reliability limit
σ_e	Standard error of estimate
$\sigma_e^{(l)}$	Acceptable standard error of estimate threshold
T_f	Frame duration
$T_{A/N}$	ACK/NAK frame duration
ϵ	Cross-over/level-crossing probability
$\Phi_2(\cdot, \cdot)$	Joint CDF of standard bivariate normal distribution
$\mathcal{D}_{\mathcal{R}}$	Data throughput of D-SW
$\mathcal{E}_{\mathcal{B}}$	Energy consumption of D-SW per successfully delivered data frame
$\mathcal{E}_{\text{Eff}}$	Energy efficiency of D-SW
D_T	Data throughput of cDIP
E_C	Energy consumption of cDIP per successfully delivered data frame
η_{cDIP}	Energy efficiency of cDIP
P_b	Bit error rate
$\mathcal{R}_{\mathcal{D}}$	Data throughput of DF-AMC
$\mathcal{E}_{\mathcal{C}}$	Per-slot average energy consumption of DF-AMC
η	Energy efficiency of DF-AMC
$\mu_n(\lambda_n)$	Average PU ‘ON’ (OFF) period of n^{th} PU
P_p	Transmit power of an active PU
P_{EH}	Harvested energy
E_{max}	Maximum SU charging capacity
E_{min}	Minimum SU energy requirement
$\Theta = \{\theta_1, \dots, \theta_N\}$	Set of N PU channels

$\Theta_I = \{\theta_i^1, \dots, \theta_i^{N_I}\}$	Set of N_I PU idle channels
$\Theta_B = \{\theta_b^1, \dots, \theta_b^{N_B}\}$	Set of N_B PU idle channels
$D_{\max}$	Maximum delay bound
$\mathcal{M} = \{m_1, m_2, \dots, m_{ \mathcal{M} }\}$	M-QAM constellation adopted by SU
$R_j \forall j = 1, \dots, \mathcal{M} $	Data rate of j^{th} modulation scheme from $\mathcal{M}$
$X_{T_k} \forall k = 0, \dots, \mathcal{M} - 2$	Thresholds for channel adaptive modulation at SU-Tx
$P_t(P_{\text{idle}})$	Data transmission power (Idling power) of SU
$\tau(j)$	Time required for transmission with j^{th} modulation scheme
$E_{\text{req}}(j)$	Energy required for transmission with j^{th} modulation scheme
$\theta_{i,k}^{\text{Tx}}$	Channel that SU chooses for transmission using a constellation of size m_{k+1}
θ_b^{H}	Channel that SU chooses for harvesting when it does not have sufficient energy for transmission
θ_b^{HN}	Channel that SU chooses for harvesting when $E(t) < E_{\max}$ and there is no data for transmission
θ_b^{C}	Intermediate choice of SU for energy harvesting
ψ	PU activity duty cycle
δ	PU error threshold
h_{ps}	Channel gain between the PU and SU
D_{R}	Data rate of proposed EH-CRN protocol
E_{EC}	Energy consumption of proposed EH-CRN protocol per unit successful data delivery
η_{CR}	Energy efficiency of proposed EH-CRN protocol