PERFORMANCE ANALYSIS OF SPECTRALLY EFFICIENT NOMA IN COOPERATIVE NETWORKS WITH BATTERY-ASSISTED ENERGY-HARVESTING NODES

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by

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Certificate

This is to certify that the thesis entitled **"PERFORMANCE ANALYSIS OF SPECTRALLY EFFICIENT NOMA IN COOPERATIVE NETWORKS WITH BATTERY-ASSISTED ENERGY-HARVESTING NODES"** being submitted by **Mr. Mudasir Ahmad Bakshi** to the Bharti School of Telecommunication Technology and Management, **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy**, is the result of genuine research work conducted under our supervision. In our assessment, the thesis meets the required standards to fulfil the degree regulations.

The findings presented in this thesis have yet to be previously submitted, either in part or in full, to any other university or institute to obtain any degree or diploma.

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Abstract

Power domain non-orthogonal multiple access (NOMA) has been generally acknowledged as a potential contender for the next generation of wireless communication systems. Due to the explosive rise of multimedia applications, spectrum scarcity is one of the most severe difficulties facing wireless communication networks. NOMA, the latest member of the multiple access family, has been suggested for the long-term evolution of the third-generation partnership project (3GPP). Over the past decade, various multiple access technologies have been extensively researched. One of the most promising options is NOMA due to its exceptional spectral efficiency (SE), low latency and capacity to support extensive connectivity. Recently proposed technologies, such as relayed NOMA (R-NOMA), cooperative NOMA (C-NOMA), and coordinated direct and relay transmission (CDRT-NOMA), can improve reliability, quality of service (QoS) and coverage area.

The demand for prolonging the battery lifespan of low-power machine-type devices (MTDs) has grown due to internet of things (IoT) and machine-to-machine (M2M) communication integration into 5G networks. To mitigate the need for frequent battery replacements, implementing self-sustaining communication nodes by harvesting energy from the radio frequency (RF) signals is highly motivated. This study systematically examines emerging technology of NOMA, including fundamentals, performance analysis (outage probability, ergodic rate, and energy efficiency (EE)), C-NOMA, and combination with simultaneous wireless information and power transfer (SWIPT) and battery-assisted EH nodes. The primary objectives of this research work are: (1) To investigate the performance of NOMA-based wireless networks, we will use cooperative full-duplex (FD)/half-duplex (HD) relaying. We will study the effects of co-channel

interference and *Residue interference* (RI) on these networks over realistic fading channels. (2) To analyze battery-assisted energy harvesting (EH) node performance and optimization in various networks to enhance quality of service (QoS) for SE and EE.

The first part of the thesis explores the feasibility of user relaying in NOMA networks. The study investigated systematic performance assessment measures for the outage probability, EE and ergodic rate in the FD/HD NOMA systems. In this context, this study considers the prerequisites for improving the performance of FD NOMA relaying over HD NOMA relaying and observed that the direct link (DL) plays a crucial role in enhancing the throughput and reducing the outage probability of the network. NOMA relay has proven to be more efficient than traditional OMA relaying. The correlation between EE and FD/HD NOMA systems in delay-limited/tolerant transmission modes is examined. Additionally, we have analyzed the impact of various system parameters on the performance of our system.

The second part of the thesis analyses the performance and optimization of battery-assisted EH nodes in C-NOMA networks. The aim is to improve the QoS regarding SE and EE. The battery energy consumed depends on the battery energy management scheme used in battery-assisted EH nodes. The study considers the fixed battery energy scheme, in which a fixed amount of battery energy is drawn in each symbol interval. This scheme is preferred due to its low implementation complexity. The research analyses the effectiveness of a C-NOMA system that incorporates SWIPT and battery-assisted non-linear energy harvesting (NL-EH). The study aims to investigate the system's outage, throughput and EE performance. Our research has shown that selecting the best combination of battery energy and power splitting parameter is crucial for achieving optimal throughput and EE. Due to the rapid growth in low-power devices within communication networks, this thesis contributes significantly to analyzing and optimizing NOMA signalling in C-NOMA networks. The research insights are valuable for system designers aiming to optimize throughput performance and battery life in light of increasing user density and the demand for improved SE and EE.

अमूर्त

पावर डोमेन नॉन-ऑर्थोगोनल मल्टीपल एक्सेस (NOMA) को आम तौर पर वायरलेस संचार प्रणालियों की अगली पीढ़ी के लिए संभावित दावेदार के रूप में स्वीकार किया गया है। मल्टीमीडिया अनुप्रयोगों के विस्फोटक उदय के कारण, स्पेक्ट्रम की कमी वायरलेस संचार नेटवर्क के सामने सबसे गंभीर कठिनाइयों में से एक है। मल्टीपल एक्सेस परिवार के नवीनतम सदस्य NOMA को तीसरी पीढ़ी की साझेदारी परियोजना (3GPP) के दीर्घकालिक विकास के लिए सुझाया गया है। पिछले दशक में, विभिन्न मल्टीपल एक्सेस तकनीकों पर बड़े पैमाने पर शोध किया गया है। सबसे आशाजनक विकल्पों में से एक NOMA है, इसकी असाधारण स्पेक्ट्रल दक्षता (SE), कम विलंबता और व्यापक कनेक्टिविटी का समर्थन करने की क्षमता के कारण। हाल ही में प्रस्तावित तकनीकें, जैसे कि रिले NOMA (R-NOMA), सहकारी NOMA (C-NOMA), और समन्वित प्रत्यक्ष और रिले ट्रांसमिशन (CDRT-NOMA), विश्वसनीयता, सेवा की गुणवत्ता (QoS) और कवरेज क्षेत्र में सुधार कर सकती हैं।

5G नेटवर्क में इंटरनेट ऑफ़ थिंग्स (IoT) और मशीन-टू-मशीन (M2M) संचार एकीकरण की वजह से कम-पावर मशीन-प्रकार के उपकरणों (MTD) की बैटरी के जीवनकाल को बढ़ाने की मांग बढ़ी है। बार-बार बैटरी बदलने की ज़रूरत को कम करने के लिए रेडियो फ़्रीक्वेंसी (RF) सिग्नल से ऊर्जा प्राप्त करके आत्मनिर्भर संचार नोड्स को लागू करना अत्यधिक प्रेरित है। यह अध्ययन NOMA की उभरती तकनीक की व्यवस्थित रूप से जाँच करता है, जिसमें बुनियादी बातें, प्रदर्शन विश्लेषण (आउटेज संभावना, एर्गोडिक दर, और ऊर्जा दक्षता (EE)), C-NOMA, और एक साथ वायरलेस सूचना और पावर ट्रांसफर (SWIPT) और बैटरी-सहायता प्राप्त EH नोड्स का संयोजन शामिल है। इस शोध कार्य के प्राथमिक उद्देश्य हैं: (1) NOMA-आधारित वायरलेस नेटवर्क के प्रदर्शन की जाँच (2) एसई और ईई के लिए सेवा की गुणवत्ता (क्यूओएस) बढ़ाने के लिए विभिन्न नेटवर्क में बैटरी-सहायता प्राप्त ऊर्जा संचयन (ईएच) नोड प्रदर्शन और अनुकूलन का विश्लेषण करना।

थीसिस का पहला भाग NOMA नेटवर्क में उपयोगकर्ता रिलेइंग की व्यवहार्यता का पता लगाता है। अध्ययन ने FD/HD NOMA सिस्टम में आउटेज संभावना, EE और एर्गोडिक दर के लिए व्यवस्थित प्रदर्शन मूल्यांकन उपायों की जांच की। इस संदर्भ में, यह अध्ययन HD NOMA रिलेइंग पर FD NOMA रिलेइंग के प्रदर्शन को बेहतर बनाने के लिए आवश्यक शर्तों पर विचार करता है और पाया है कि डायरेक्ट लिंक (DL) थ्रूपुट को बढ़ाने और नेटवर्क की आउटेज संभावना को कम करने में महत्वपूर्ण भूमिका निभाता है। NOMA रिले पारंपरिक OMA रिलेइंग की तुलना में अधिक कुशल साबित हुई है। विलंब-सीमित/सहिष्णु संचरण मोड में EE और FD/HD NOMA सिस्टम के बीच सहसंबंध की जांच की गई है। इसके अतिरिक्त, हमने अपने सिस्टम के प्रदर्शन पर विभिन्न सिस्टम मापदंडों के प्रभाव का विश्लेषण किया है।

थीसिस का दूसरा भाग C-NOMA नेटवर्क में बैटरी-सहायता प्राप्त EH नोड्स के प्रदर्शन और अनुकूलन का विश्लेषण करता है। इसका उद्देश्य SE और EE के संबंध में QoS में सुधार करना है। बैटरी द्वारा खपत की जाने वाली ऊर्जा बैटरी-सहायता प्राप्त EH नोड्स में उपयोग की जाने वाली बैटरी ऊर्जा प्रबंधन योजना पर निर्भर करती है। अध्ययन निश्चित बैटरी ऊर्जा योजना पर विचार करता है, जिसमें प्रत्येक प्रतीक अंतराल में बैटरी ऊर्जा की एक निश्चित मात्रा खींची जाती है। इस योजना को इसके कम कार्यान्वयन जटिलता के कारण पसंद किया जाता है। शोध एक C-NOMA सिस्टम की प्रभावशीलता का विश्लेषण करता है जिसमें SWIPT और बैटरी-सहायता प्राप्त गैर-रेखीय ऊर्जा संचयन (NL-EH) शामिल है। अध्ययन का उद्देश्य सिस्टम के आउटेज, थ्रूपुट और EE प्रदर्शन की जांच करना है। हमारे शोध से पता चला है कि बैटरी ऊर्जा और पावर स्प्लिटिंग पैरामीटर का सबसे अच्छा संयोजन चुनना इष्टतम थ्रूपुट और EE प्राप्त करने के लिए महत्वपूर्ण है। संचार नेटवर्क के भीतर कम-शक्ति वाले उपकरणों में तेजी से वृद्धि के कारण, यह थीसिस C-NOMA नेटवर्क में NOMA सिग्नलिंग का विश्लेषण और अनुकूलन करने में महत्वपूर्ण योगदान देती है। शोध से प्राप्त अंतर्दृष्टि उन सिस्टम डिजाइनरों के लिए मूल्यवान है, जो बढ़ते उपयोगकर्ता घनत्व और बेहतर एसई और ईई की मांग के मद्देनजर थ्रूपुट प्रदर्शन और बैटरी जीवन को अनुकूलित करने का लक्ष्य रखते हैं।

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Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
ADC	Analog to Digital Converter
AF	Amplify-and-Forward
ATSC	Advanced Television Systems Committee
AWGN	Additive White Gaussian Noise
B5G	Beyond Fifth Generation
BPCU	Bits Per Channel Use
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CDRT	Coordinated Direct and Relay Transmission
C-NOMA	Cooperative Non-orthogonal Multiple Access
C-OMA	Cooperative orthogonal Multiple Access
CSI	Channel State Information
D2D	Device-to-Device
DBE	Dynamic Battery Energy
DC	Direct Current
DAC	Digital to Analog Converter

DF	Decode-and-Forward
DL	Direct Link
DPA	Dynamic Power Allocation
EDGE	Enhanced Data GSM Evolution
EE	Energy Efficiency
EH	Energy Harvesting
ETSI	European Telecommunications Standards Institute
FD	Full-Duplex
FDR	Full-Duplex Relay
FDMA	Non-Buffer-Aided
FPA	Fixed Power Allocation
FU	Far User
Gbps	Gigabits Per Second
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HD	Half-Duplex
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IIT	Indian Institute f Technology
IoT	Internet of Things
IR	Incremental Relaying
IRS	Intelligent Reflecting Surface
IT	Information Transmission
ITU	International Telecommunication Union
Kbps	Kilobits Per Second
LDM	Layered Division Multiplexing
L-EH	Linear Energy Harvesting
LPWA	Low Powered Wide Area
LI	Self-loop interference

LTE	Long-Term Evolution
LTE-A	Long-Term Evolution-Advanced
MBB	Mobile Broadband
Mbps	Megabits Per Second
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
mMTC	Massive Machine Type Communication
MTD	Machine Type Device
MUST	Multi-User Superposition Transmission
NB-IoT	Narrowband Internet of Things
NDL	NO Direct Link
NL-EH	Non-Linear Energy Harvesting
NFC	Near-field Communication
NOMA	Non-orthogonal Multiple Access
NR	New Radio
NU	Near User
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Orthogonal Multiple Access
PDF	Probability Density Function
PS	Power Splitting
QoS	Quality of Service
RF	Radio Frequency
R-NOMA	Relayed Non-orthogonal Multiple Access
RI	Residual interference
RV	Random Variable
SC	Superposition coding
SDMA	Spatial Division Multiple Access
SDR	Software-defined Radio
SE	Spectral Efficiency
SIC	Successive Interference Cancellation

SINR	Signal-to-Interference-Plus-Noise-Ratio
SNR	Signal-to-Noise-Ratio
SWIPT	Simultaneous Wireless Information and Power Transfer
TDMA	Time Division Multiple Access
TS	Time Switching
TSDSI	Telecommunications Standards Development Society, India
TWR	Two-Way Relay
VOIP	Voice over Internet Protocol
WET	Wireless Energy Transfer
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPN	Wireless Power Transfer

Notations

$\|\cdot\|$	Absolute value
$\|\|\mathbf{x}\|\|$	Euclidean norm of a vector $\mathbf{x}$
ρ_s	SNR
$\mathcal{CN}(\mu, \sigma^2)$	Complex circular normal distribution with mean μ and variance σ^2
$\mathcal{CN}(0, \sigma^2)$	Complex Gaussian distribution with mean 0 and variance σ^2
B	Bandwidth
D	Diversity order
E_s	Source transmit energy or symbol energy
E_n	Transmit energy at the NU
E_{in}	Available input energy at energy at EH circuit
E_{sat}	Energy saturation threshold
$e^{[\cdot]}, exp[\cdot]$	Exponential function
$E_n[\cdot]$	Generalized exponential integral for real non-zero values of order n, where $E_n[x] = \int_1^\infty t^{-n} e^{-xt} dt \qquad (n = 0, 1, 2, ...)$
$\mathbb{E}[\cdot]$	Expectation operator
$f_{\mathbf{X}}(x)$	Probability density function of random variable X
$F_{\mathbf{X}}(x)$	Cumulative distribution function of random variable X
${}_2F_1$	Gauss hyper-geometric function
$\Gamma[\cdot]$	Gamma function defined on the complex plane except for 0 and, negative integers, $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$
$\gamma[\cdot, \cdot]$	Lower Incomplete Gamma function, where $\gamma[a, x] = \int_0^x t^{a-1} exp(-t) dt$
$\Gamma[\cdot, \cdot]$	Upper incomplete Gamma function, where $\Gamma[a, x] = \int_x^\infty t^{a-1} exp(-t) dt$
γ_{th_F}	Threshold SNR to decode the symbol of the FU

γ_{th_N}	Threshold SNR to decode the symbol of the NU
$\gamma_{D_F \rightarrow D_N}$	SINR at the NU to decode the FUs symbol
γ_{D_N}	SINR at the NU to decode its own symbol
κ	Residual interference
$max(\cdot)$	Maximum operator
$min(\cdot)$	Minimum operator
θ	Path loss exponent
m	Nakagami-m fading shape parameter
P_{D_F}	Far user outage probability
P_{D_N}	Near user outage probability
P_O	Outage probability
α	Time-switching parameter
ρ	Power-splitting parameter
P_S	Source transmit power
P_R	NU transmit power
Q_h	Harvested energy
Q_b	Battery energy
R	Target rate
R_N	Target rate to detect the NU symbol
R_F	Target rate to detect the FU symbol
R_{D_N}	Ergodic rate of the NU
R_{D_F}	Ergodic rate of the FU
η	Energy efficiency
S	High SNR slope
τ	Throughput
$\mathbf{U}(\cdot)$	Unit-step function
x_N	Transmit signal intended for the NU
x_F	Transmit signal intended for the FU
y_{D_N}	Received signal at the NU
y_{D_F}	Received signal at the FU