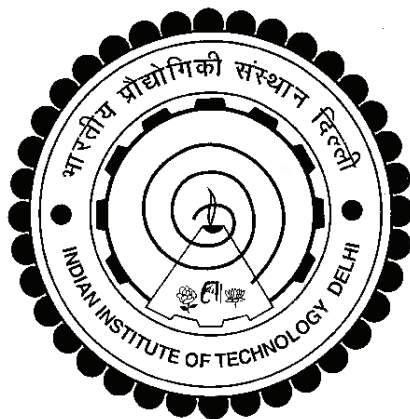


**PERFORMANCE OF COMMUNICATION
NETWORKS WITH ENERGY-BUFFER EQUIPPED
NODES**

DILEEP BAPATLA



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JULY 2021

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by

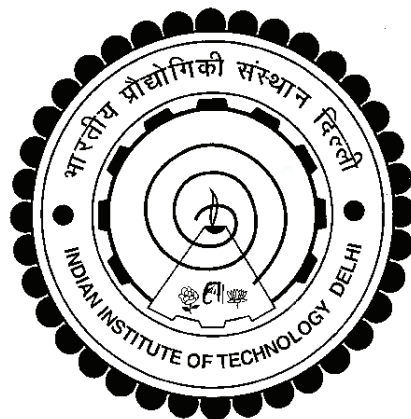
DILEEP BAPATLA

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfillment of the requirements of the degree Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

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CERTIFICATE

This is to certify that the thesis titled **Performance of Communication Networks with Energy-Buffer Equipped Nodes**, submitted by **Dileep Bapatla**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under our supervision.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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DILEEP BAPATLA

ABSTRACT

Next generation wireless communication networks need to meet the high data-rate demands of internet access, online games, and multimedia applications such as voice over internet protocol (VoIP), and video streaming. Machine type devices (MTDs) are already playing an important role in our lives. Battery lifetime issues and difficulty in battery replacement have received a large amount of research focus for this reason. Energy harvesting (EH) is often suggested as a solution. Energy can be harvested from several different freely available environmental sources such as wind, vibration, thermal, solar and ambient radio frequency (RF) signals. However, it is the use of RF sources that is considered to be most promising. The harvested energy can be stored in energy storage devices like supercapacitors or batteries. Due to rapidly increasing number of MTDs, promise of low cost, small form factor and theoretically infinite lifetime, such self-sustaining nodes are expected to play a very important role in next generation communications. Understanding performance of networks with such nodes is therefore of fundamental importance.

The main objective of this thesis is the accurate analysis of performance of wireless communication networks with energy buffer equipped self-sustaining EH nodes. All currently existing literature on cooperative communication with such EH nodes uses the discrete state space Markov chain (DSMC) to model the energy buffer although energy is continuous. This is an inaccurate representation, and requires high computational complexity to analyze performance. For this reason, in this thesis, the energy buffer states are modelled using a discrete-time continuous state space Markov chain (CSMC). The limiting or steady state distribution of the stored energy is used for analysis of the system performance, and makes it possible to obtain important insights. Use of the CSMC dramatically reduces the computational complexity required for analysis of performance, and ensures accuracy. Utilization of the harvest-store-use (HSU) architecture with energy buffers means that excess energy can be made available in future signalling intervals, ensuring better performance than with the harvest-use (HU) archi-

texture and direct (relay-less) transmission. The best-effort policy (BEP) and the on-off policy (OOP) are considered for energy management in the energy buffers.

Cooperative relaying increases the system capacity and coverage range. Generally, the nodes which act as relays deplete their battery energy quickly, and use of harvested energy at the relays is well motivated. Intuitively, it can be seen that use of the HSU architecture at the relays with energy buffers can considerably enhance performance as compared to the case when the HU architecture is used. For this reason, the performance of incremental relaying cooperative network with an energy buffer at the EH relay is studied in this thesis. In this context, use of incremental relaying is doubly advantageous. Firstly, throughput is enhanced when the direct link is itself successful. Secondly, when the direct link is successful, the relay is not utilized, and energy accumulates in the energy buffer (thereby ensuring better performance in future signalling intervals). Performance of such networks is analyzed with two different energy management policies - incremental best-effort policy (IBEP) and incremental on-off policy (IOOP). To study the system performance, the limiting distributions of energy in the energy buffer are derived with both these policies. An interesting property established in this thesis is that the diversity order attained with the IBEP is two, but that attained by the IOOP is only one. In other networks too that rely on cooperation, use of energy harvesting nodes is well motivated. For example, in cooperative non-orthogonal multiple access (NOMA) networks, expecting the near-user close the source to relay information to the distant far-user is unreasonable in some scenarios since such relaying involves use of battery energy to relay some other user's symbols. When EH is used, and the harvested energy is used for relaying by the near-user, it does not have to expend its own battery energy. Performance of cooperative NOMA networks with self-sustaining EH near-users is analyzed in this thesis. It is shown that switching between NOMA, cooperative NOMA and OMA modes in a hybrid NOMA (HN) scheme can considerably enhance throughput due to accumulation of energy in the energy buffer when relaying is not required. Limiting distributions are derived for the hybrid NOMA with BEP (HN-BEP) and OOP (HN-OOP), and used to analyze throughput performance.

The communication range of self-sustaining nodes is quite limited, and use of other self-sustaining nodes in the vicinity to relay information is of practical interest. In this thesis, the performance of a two-hop cooperative network is analyzed with green self-sustaining nodes equipped with energy buffers. Insights are derived on the choice of

energy management policies at the source and relay, the choice of target rate, and the transmit powers to be used by them. Performance with adaptive rate transmission is also analyzed.

In several sensor networks and IoT applications, a wireless node in the vicinity acts as a data collector and relays information to an access point. In this thesis, we consider such links with a self-sustaining source. Due to the large asymmetry in the links, use of intelligent link selection with data buffer at the relay is well motivated. We also analyze the performance of such networks, and demonstrate how the CSMC modelled energy buffer and the DSMC modelled data buffer can both be balanced by intelligent choice of target rates and transmit powers at the source and the relay so as to maximize the throughput of the network. In typical applications, feedback of channel state information and buffer state information is not feasible, so simple link selection schemes are evolved. In the first only-buffer-status (OBS) scheme, link selection is based on energy-buffer status alone. A modified only-buffer-status (MOBS) scheme is then suggested, and its performance is analyzed. The third scheme uses both energy-buffer status and first-hop channel knowledge for link selection. Expressions are derived for throughput and limiting distributions of stored energy with all the three schemes.

In order to understand the influence of interference on performance of links with self-sustaining nodes, the performance of full-duplex communication link between two energy-buffer equipped nodes is analyzed. It is demonstrated how the choice of transmit powers and target rates of each node are influenced by the self-interference. Interestingly, it is demonstrated that due to the presence of self-interference, sum throughput of the nodes is maximized when the energy buffers are starved. The energy management policy that should be chosen at each node to maximize the sum throughput depends on the self-interference levels, as well as on the mean harvested energy levels.

The thesis makes important contributions to analysis of performance of communication links with self-sustaining nodes. Due to rapid increase in number of MTDs, the insights obtained will be useful in design of next generation communication systems.

सार

अगली पीढ़ी के वायरलेस संचार नेटवर्क को इंटरनेट एक्सेस, ऑनलाइन गेम और मल्टीमीडिया एप्लिकेशन जैसे वॉयस ओवर की उच्च डेटा-दर मांगों को पूरा करने की आवश्यकता है। इंटरनेट प्रोटोकॉल (वीओआईपी), और वीडियो स्ट्रीमिंग। मशीन प्रकार के उपकरण (एमटीडी) पहले से ही हमारे जीवन में एक महत्वपूर्ण भूमिका निभा रहे हैं। बैटरी लाइफटाइम की समस्याएं और कठिनाई इस कारण से बैटरी प्रतिस्थापन को बड़ी मात्रा में शोध फोकस प्राप्त हुआ है। ऊर्जा संग्रहण (ईएच) को अक्सर समाधान के रूप में सुझाया जाता है। ऊर्जा से काटा जा सकता है कई अलग-अलग स्वतंत्र रूप से उपलब्ध पर्यावरणीय स्रोत जैसे हवा, कंपन, थर्मल, सौर और परिवेश रेडियो फ्रीक्वेंसी (आरएफ) सिग्नल। हालांकि, यह आरएफ का उपयोग है स्रोत जिन्हें सबसे अधिक आशाजनक माना जाता है। एकत्रित ऊर्जा को में संग्रहित किया जा सकता है सुपरकैपेसिटर या बैटरी जैसे ऊर्जा भंडारण उपकरण में। तेजी से बढ़ती संख्या के कारण एमटीडी की, कम लागत का वादा, छोटा रूप कारक और सैद्धांतिक रूप से अनंत जीवनकाल, इस तरह के आत्मनिर्भर नोड्स से संचार की अगली पीढ़ी में बहुत महत्वपूर्ण भूमिका निभाने की उम्मीद है ऐसे नोड्स वाले नेटवर्क के प्रदर्शन को समझने का मौलिक महत्व इसलिए है।

इस थीसिस का मुख्य उद्देश्य वायरलेस के प्रदर्शन का सटीक विश्लेषण है ऊर्जा बफर के साथ संचार नेटवर्क आत्मनिर्भर ईएच नोड्स से लैस है। सभी ऐसे ईएच नोड्स के साथ सहकारी संचार पर वर्तमान में मौजूदा साहित्य का उपयोग करता है ऊर्जा बफर को मॉडल करने के लिए असतत राज्य अंतरिक्ष मार्कोव श्रृंखला (डीएसएमसी) हालांकि ऊर्जा निरंतर है। यह एक गलत प्रतिनिधित्व है, और उच्च कम्प्यूटेशनल की आवश्यकता है प्रदर्शन का विश्लेषण करने के लिए जटिलता। इस कारण से, इस थीसिस में, ऊर्जा बफर राज्यों को असतत-समय निरंतर राज्य स्थान मार्कोव श्रृंखला का उपयोग करके तैयार किया जाता है (सीएसएमसी)। संग्रहित ऊर्जा का सीमित या स्थिर अवस्था वितरण विश्लेषण के लिए उपयोग किया जाता है प्रणाली के प्रदर्शन का, और महत्वपूर्ण अंतर्दृष्टि प्राप्त करना संभव बनाता है। उपयोग सीएसएमसी के विश्लेषण के लिए आवश्यक कम्प्यूटेशनल जटिलता को नाटकीय रूप से कम करता है प्रदर्शन की, और सटीकता सुनिश्चित करता है। फसल-भंडार-उपयोग (एचएसयू) वास्तुकला का उपयोग ऊर्जा बफर के साथ का अर्थ है कि भविष्य में अतिरिक्त ऊर्जा उपलब्ध कराई जा सकती है सिग्नलिंग अंतराल, फसल-उपयोग (एचयू) वास्तुकला और प्रत्यक्ष (रिले-कम) संचरण की तुलना में बेहतर प्रदर्शन सुनिश्चित करना। सर्वोत्तम प्रयास नीति (बीईपी) और ऑन-ऑफ ऊर्जा बफर में ऊर्जा प्रबंधन के लिए नीति (ओओपी) पर विचार किया जाता है।

सहकारी रिलेइंग सिस्टम की क्षमता और कवरेज रेंज को बढ़ाता है। आम तौर पर, नोड्स जो रिले के रूप में कार्य करते हैं, उनकी बैटरी ऊर्जा को जल्दी से समाप्त कर देते हैं, ऊर्जा की संग्रहण का उपयोग रिले में अच्छी तरह से प्रेरित है। सहज रूप से, यह देखा जा सकता है कि एचएसयू का उपयोग ऊर्जा बफर्स के साथ रिले में आर्किटेक्चर प्रदर्शन को काफी बढ़ा सकता है उस मामले की तुलना में जब एचयू वास्तुकला का उपयोग किया जाता है। इस वजह से प्रदर्शन ईएच पर ऊर्जा बफर के साथ वृद्धिशील रिलेइंग सहकारी नेटवर्क का इस थीसिस में रिले का अध्ययन किया जाता है। इस संदर्भ में, वृद्धिशील रिलेइंग का उपयोग दोगुना है लाभप्रद सबसे पहले, थ्रूपुट बढ़ाया जाता है जब सीधा लिंक स्वयं सफल होता है। दूसरे, जब सीधा लिंक सफल होता है, तो रिले का उपयोग नहीं किया जाता है, और ऊर्जा जमा होती है ऊर्जा बफर में (जिससे भविष्य के सिग्नलिंग में बेहतर प्रदर्शन सुनिश्चित होता है अंतराल)। ऐसे नेटवर्क के प्रदर्शन का विश्लेषण दो अलग-अलग ऊर्जा प्रबंधन के साथ किया जाता है नीतियां - वृद्धिशील सर्वोत्तम प्रयास नीति (आईबीईपी) और वृद्धिशील ऑन-ऑफ नीति (आईओओपी)। प्रणाली के प्रदर्शन का अध्ययन करने के लिए, में ऊर्जा के सीमित वितरण इन दोनों नीतियों के साथ ऊर्जा बफर प्राप्त किया जाता है। एक दिलचस्प संपत्ति की स्थापना इस थीसिस में यह है कि आईबीईपी के साथ प्राप्त विविधता क्रम दो है, लेकिन वह प्राप्त हुआ आईओओपी केवल एक है। अन्य नेटवर्क में भी जो सहयोग पर निर्भर हैं, ऊर्जा संचयन का उपयोग नोड्स

अच्छी तरह से प्रेरित हैं। उदाहरण के लिए, सहकारी गैर-ऑर्थोगोनल मल्टीपल में एक्सेस (एनओएमए) नेटवर्क, निकट-उपयोगकर्ता से सूचना को रिले करने के लिए स्रोत को बंद करने की अपेक्षा करना दूर-दूर के उपयोगकर्ता के लिए कुछ परिदृश्यों में अनुचित है क्योंकि इस तरह के रिलेइंग में उपयोग शामिल है किसी अन्य उपयोगकर्ता के प्रतीकों को रिले करने के लिए बैटरी ऊर्जा का। जब ईएच का उपयोग किया जाता है, और काटा जाता है ऊर्जा का उपयोग निकट-उपयोगकर्ता द्वारा रिले करने के लिए किया जाता है, इसे स्वयं खर्च करने की आवश्यकता नहीं होती है बैटरी ऊर्जा। आत्मनिर्भर ईएच. के साथ सहकारी एनओएमए नेटवर्क का प्रदर्शन इस थीसिस में निकट-उपयोगकर्ताओं का विश्लेषण किया गया है। यह दिखाया गया है कि एनओएमए, सहकारी के बीच स्विच करना एक संकर एनओएमए (एचएन) योजना में एनओएमए और ओएमए मोड काफी हद तक हो सकते हैं रिले करते समय ऊर्जा बफर में ऊर्जा के संचय के कारण थ्रूपुट बढ़ाएं आवश्यक नहीं। सीमित वितरण बीईपी (एचएन-बीईपी) और ओओपी (एचएन-ओओपी) के साथ हाइब्रिड एनओएमए के लिए व्युत्पन्न होते हैं, और थ्रूपुट प्रदर्शन का विश्लेषण करने के लिए उपयोग किया जाता है।

आत्मनिर्भर नोड्स की संचार सीमा काफी सीमित है, और अन्य का उपयोग सूचना को रिले करने के लिए आसपास के क्षेत्र में आत्मनिर्भर नोड्स व्यावहारिक रुचि का है। इसमें थीसिस, दो-हॉप सहकारी नेटवर्क के प्रदर्शन का विश्लेषण हेर आत्मनिर्भरता के साथ किया जाता है ऊर्जा बफर से लैस नोड्स। स्रोत और रिले पर ऊर्जा प्रबंधन नीतियों की पसंद, लक्ष्य दर की पसंद, और पर अंतर्दृष्टि प्राप्त की जाती है उनके द्वारा उपयोग की जाने वाली शक्तियों को संचारित करें। अनुकूली दर संचरण के साथ प्रदर्शन है विश्लेषण भी किया।

कई सेंसर नेटवर्क और आईओटी अनुप्रयोगों में, आसपास के क्षेत्र में एक वायरलेस नोड डेटा संग्राहक के रूप में कार्य करता है और सूचना को एक एक्सेस प्वाइंट तक पहुंचाता है। इस थीसिस में, हम एक आत्मनिर्भर स्रोत के साथ ऐसे संबंधों पर विचार करें। में बड़ी विषमता के कारण लिंक, रिले में डेटा बफर के साथ बुद्धिमान लिंक चयन का उपयोग अच्छी तरह से प्रेरित है। हम ऐसे नेटवर्क के प्रदर्शन का भी विश्लेषण करते हैं, और प्रदर्शित करते हैं कि सीएसएमसी मॉडलिंग किए गए ऊर्जा बफर और डीएसएमसी मॉडल किए गए डेटा बफर दोनों को संतुलित किया जा सकता है लक्ष्य दरों का बुद्धिमान विकल्प और स्रोत और रिले पर शक्ति संचारित करना ताकि नेटवर्क के थ्रूपुट को अधिकतम करें। विशिष्ट अनुप्रयोगों में, चैनल की प्रतिक्रिया राज्य की जानकारी और बफर राज्य की जानकारी संभव नहीं है, इसलिए सरल लिंक चयन योजनाएं विकसित की हैं। पहली एकमात्र-बफर-स्थिति (ओबीएस) योजना में, लिंक चयन है अकेले ऊर्जा-बफर स्थिति के आधार पर। एक संशोधित केवल-बफर-स्थिति (एमओबीएस) योजना है फिर सुझाव दिया जाता है, और इसके प्रदर्शन का विश्लेषण किया जाता है। तीसरी योजना दोनों एनर्जीबफर का उपयोग करती है लिंक चयन के लिए स्थिति और प्रथम-हॉप चैनल ज्ञान। व्यंजक व्युत्पन्न होते हैं तीनों योजनाओं के साथ संग्रहित ऊर्जा के थ्रूपुट और सीमित वितरण के लिए।

दखल अंदाजी के साथ लिंक के प्रदर्शन पर हस्तक्षेप के प्रभाव को समझने के लिए आत्मनिर्भर नोड्स, दो के बीच पूर्ण-द्वैध संचार लिंक का प्रदर्शन ऊर्जा-बफर सुसज्जित नोड्स का विश्लेषण किया जाता है। यह प्रदर्शित किया जाता है कि कैसे संचारण का चुनाव प्रत्येक नोड की शक्तियां और लक्ष्य दरें आत्म-हस्तक्षेप से प्रभावित होती हैं। दिलचस्प है, यह प्रदर्शित किया जाता है कि आत्म-हस्तक्षेप की उपस्थिति के कारण, का योग थ्रूपुट ऊर्जा बफर्स भूखे रहने पर नोड्स को अधिकतम किया जाता है। ऊर्जा प्रबंधन कुल थ्रूपुट को अधिकतम करने के लिए प्रत्येक नोड पर चुनी जाने वाली नीति पर निर्भर करता है आत्म-हस्तक्षेप के स्तर, साथ ही साथ ऊर्जा के औसत स्तर पर।

थीसिस संचार के प्रदर्शन के विश्लेषण में महत्वपूर्ण योगदान देता है आत्मनिर्भर नोड्स के साथ लिंक। एमटीडी की संख्या में तेजी से वृद्धि के कारण, प्राप्त अंतर्दृष्टि अगली पीढ़ी की संचार प्रणालियों के डिजाइन में उपयोगी होगी।

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ABBREVIATIONS

2G	2 nd Generation
3G	2 nd Generation
3GPP	3 rd Generation Partnership Project
4G	4 th Generation
5G	5 th Generation
ACK	(Positive) Acknowledgement
AF	Amplify and Forward
AP	Access point
BEP	Best-effort policy
BS	Base station
BPSK	Binary phase shift keying
CDF	Cumulative distribution function
CSMC	Continuous state space Markov chain
CSS	Chirp spread spectrum
DF	Decode and Forward
DSMC	Discrete state space Markov chain
DSSS	Direct-sequence spread spectrum (DSSS)
DT	Direct transmission
ECG	Electrocardiography
EH	Energy harvesting
ETSI	European Telecommunication Standards Institute
FD	Full-duplex
FDR	Full-duplex relaying
FU	Far-user
HARQ	Hybrid automatic repeat request
HD	Half-duplex
HN	Hybrid non-orthogonal multiple access
HSU	Harvest store use

HU	Harvest use
IBEP	Incremental best-effort policy
IOOP	Incremental on-off policy
IoT	Internet of Things
ISM	Industrial, scientific and medical
LTE	Long term evaluation
LTE-A	Long term evaluation-advanced
MRC	Maximal ratio combining
MIMO	Multiple input multiple output
NACK	Negative acknowledgement
NB-IoT	Narrow band internet of things
NOMA	Non orthogonal multiple access
NU	Near-user
OFDMA	Orthogonal frequency division multiple access
OMA	Orthogonal multiple access
OOP	On-off policy
PDF	Probability density function
PEB	Primary energy buffer
QPSK	Quadrature phase shift keying
QoS	Quality of service
RF	Radio frequency
SEB	Secondary energy buffer
SI	self-interference
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal to noise ratio
SWIPT	Simultaneous wireless information and power transfer (SWIPT)
TV	Television
WCDMA	Wide band code division multiple access

NOTATION

$ \cdot $	Absolute value
$F_X(\cdot)$	Cumulative distribution function of random variable X
$\mathcal{CN} \sim (\mu, \sigma^2)$	Circular complex Gaussian distribution with mean μ and variance σ^2
$B(i)$	Energy buffer level in the i^{th} signalling interval
$E_n(\cdot)$	Exponential integral function of order n
$\mathbb{E}(\cdot)$	Expectation operator
$X(i)$	Harvested energy in the i^{th} signalling interval
$\ \cdot\ $	l_2 norm
$Q(i)$	Level of data buffer in the i^{th} time slot
$\ln(x)$	Natural logarithm of x
P_{Out}	Outage probability
α	Path loss exponent
β	Power allocation factor
$\mathcal{W}(\cdot)$	Principal branch of the Lambert-W function
$\Pr(\cdot)$	Probability of an event
P_R	Relay transmit power
E_R	Relay energy
Ψ_{11}	Self interference at device D_1
Ψ_{22}	Self interference at device D_2
P_s	Source transmit power
$\Gamma(\cdot, \cdot)$	Upper incomplete Gamma function
σ^2	Variance of additive White Gaussian noise