

PERFORMANCE OF DOWNLINK NETWORKS WITH SPECTRALLY EFFICIENT NON-ORTHOGONAL MULTIPLE ACCESS SIGNALLING

ANAND JEE



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

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by

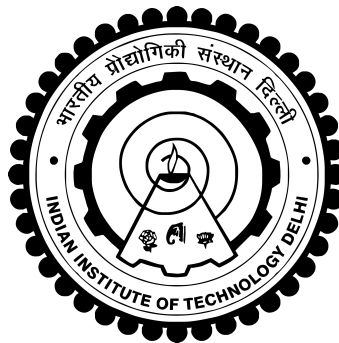
ANAND JEE

DEPARTMENT OF ELECTRICAL ENGINEERING

submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to

***My caring family, my dedicated supervisor, and
my beloved friends.***

**“Success is not final, failure is not fatal: It is the courage
to continue that counts.”**

- *Winston Churchill*

CERTIFICATE

This is to certify that the thesis entitled “**Performance of Downlink Networks With Spectrally Efficient Non-Orthogonal Multiple Access Signalling**”, submitted by **Mr. Anand Jee**, to the Department of Electrical Engineering, 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 my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

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.

Dr. Shankar Prakriya

Professor

Department of Electrical Engineering

Indian Institute of Technology, Delhi

Hauz Khas, New Delhi, 110016

Date:

Place: New Delhi

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Date:

Anand Jee

ABSTRACT

The next-generation of wireless networks is essential to meet the requirements of high data rates and massive connectivity. These networks are fundamentally important for improving various aspects of our daily lives through Internet of Things (IoT) applications such as smart homes, wearable devices, advanced power grids, industry 4.0 technologies, smart education, and multimedia applications like voice over internet protocol (VoIP) and video streaming. Machine-type devices (MTDs) are already playing a significant role in our everyday lives, and their number is expected to explode in the coming years. Due to their sheer number, the existing orthogonal multiple access (OMA) techniques (widely used in older generations of wireless networks) are unfit to meet the uncompromising future requirements on user density and network traffic. Numerous multiple access technologies have been extensively studied over the past decade for this reason. Among these, non-orthogonal multiple access (NOMA) has emerged as a highly promising option due to its exceptional spectral efficiency (SE), low latency, and capacity to support extensive connectivity. Technologies like relayed NOMA (R-NOMA), Cooperative NOMA (C-NOMA), and coordinated direct and relay transmission (CDRT) NOMA have recently been proposed to enhance reliability, quality of service (QoS), and coverage area. Due to acute spectrum shortage, the use of cognitive radio (CR), especially of the underlay type, is advantageous. The performance of NOMA signalling in such underlay networks is therefore of considerable interest.

CDRT-NOMA and C-NOMA techniques presented in literature attempt to improve performance at a distant far-user (FU) at the expense of a near-user (NU) by signalling to both users together. Without use of incremental signalling techniques, a diversity of two can be achieved by the FU with CDRT-NOMA, but not by the NU. In this thesis, we attempt to improve the performance of the NU too. This motivates it to participate in NOMA signalling to assist a distant FU. Note however that the power allocated to the NU symbols can alternatively be reduced, and that of the FU increased (thereby enhancing FU performance). Further, we develop a technique for combining along with successive interference cancellation (SIC) to allow the NU also to attain a diversity of

two, and analyze the performance. Performance of the suggested scheme is shown to be markedly superior in terms of both SE and energy efficiency (EE). In addition, analysis of performance for the underlay CDRT-NOMA network is also presented. It is further shown that use of incremental signalling in CDRT-NOMA network can further improve both SE and EE, and some important insights are drawn on the performance.

CR is another promising technology that attempts to overcome the problem of limited radio resources by allowing spectrum sharing, thereby improving overall spectrum utilization efficiency. Both cooperative communication and CR aim to improve the SE. However in underlay CR (unlike in traditional cooperative communication), the transmit powers are constrained by the interference temperature limit (ITL), and are therefore random due to the peak interference type of power control. The performance of NOMA in such scenarios can therefore be poor. It is shown in this thesis that network adaptation by switching between NOMA and OMA, along with user selection, is the key to achieving good performance despite the power constraints. It is shown that by leveraging limited knowledge of the primary channel through a channel state information (CSI) dependent ITL, very significant gains in throughput can be achieved over the case of static ITL. Closed-form expressions for power allocation are presented, along with insights into selecting optimal parameters to maximize performance.

In a multiple access network, it is shown in this thesis that due to the fading nature of channels, network adaptation by mode switching between OMA, NOMA and C-NOMA is the key to attaining good performance. It is further shown that when a simple user selection scheme is used along with mode switching, very good performance can be obtained at the distant users. In the statistical fixed power allocation (FPA) scheme, it is shown how the power allocation can be chosen based on statistical properties of the channels alone to maximize the throughput performance. It is then shown that when channel knowledge is available, it can be used to determine the NOMA power allocations to further improve performance with intelligent user selection and mode switching. This channel-aware scheme is referred to as the dynamic power allocation (DPA) scheme. It is further shown that the DPA scheme can lead to energy savings. Closed-form expressions for the outage probability, throughput, and EE are derived for both the FPA and the DPA schemes. This thesis shows that despite strict constraints on the transmit power of the secondary transmitter, high throughput can be achieved in underlay CRNs using intelligent user selection and switching strategies. Furthermore, this

thesis emphasizes the importance of intelligent channel-aware techniques for achieving performance goals.

In a downlink multiuser NOMA network, it is shown in this thesis that exploiting channel knowledge at the source can lead to dramatic improvements in SE as well as EE. An optimal user subset selection mechanism is developed. In addition, the optimum NOMA power allocation parameters are expressed in closed-form using channel knowledge, and the throughput performance is analyzed. It is demonstrated how the transmit power at the source can be optimally chosen based on this channel knowledge to maximize EE.

This thesis makes significant contributions to the analysis and optimization of cooperative and cognitive communication systems based on NOMA signalling. Due to increasing user density and the need for enhanced SE and EE, the insights obtained are extremely valuable for system designers.

सार

उच्च डेटा दरों और व्यापक कनेक्टिविटी की आवश्यकताओं को पूरा करने के लिए वायरलेस नेटवर्क की अगली पीढ़ी आवश्यक है। ये नेटवर्क इंटरनेट ऑफ थिंग्स (आईओटी) अनुप्रयोगों जैसे स्मार्ट होम, पहनने योग्य उपकरण, उन्नत पावर ग्रिड, उद्योग 4.0 प्रौद्योगिकियों, स्मार्ट शिक्षा और वॉयस ओवर इंटरनेट प्रोटोकॉल (वीओआईपी) और वीडियो स्ट्रीमिंग जैसे मल्टीमीडिया अनुप्रयोगों के माध्यम से हमारे दैनिक जीवन के विभिन्न पहलुओं को बेहतर बनाने के लिए मौलिक रूप से महत्वपूर्ण हैं। मशीन-प्रकार के उपकरण (एमटीडी) पहले से ही हमारे रोजमर्रा के जीवन में महत्वपूर्ण भूमिका निभा रहे हैं, और आने वाले वर्षों में उनकी संख्या बढ़ने की उम्मीद है। उनकी विशाल संख्या के कारण, मौजूदा ऑर्थोगोनल मल्टीपल एक्सेस (ओमा) तकनीकें (वायरलेस नेटवर्क की पुरानी पीढ़ियों में व्यापक रूप से उपयोग की जाती हैं) उपयोगकर्ता घनत्व और नेटवर्क ट्रैफ़िक पर भविष्य की आवश्यकताओं को पूरा करने के लिए अनुपयुक्त हैं। इस कारण से पिछले दशक में कई मल्टीपल एक्सेस तकनीकों का बड़े पैमाने पर अध्ययन किया गया है। इनमें से, नौन-ऑर्थोगोनल मल्टीपल एक्सेस (नोमा) अपनी असाधारण वर्णक्रमीय दक्षता (एसई), कम विलंबता और व्यापक कनेक्टिविटी का समर्थन करने की क्षमता के कारण एक अत्यधिक आशाजनक विकल्प के रूप में उभरा है। रिलेड नोमा (आर- नोमा), सहकारी नोमा (सी- नोमा), और समन्वित प्रत्यक्ष और रिले ट्रांसमिशन (सीडीआरटी) नोमा जैसी प्रौद्योगिकियों को हाल ही में विश्वसनीयता, सेवा की गुणवत्ता (क्यूओएस) और कवरेज क्षेत्र को बढ़ाने के लिए में प्रस्तावित किया गया है। स्पेक्ट्रम की गंभीर कमी के कारण, विशेष रूप से अंडरले प्रकार के संज्ञानात्मक रेडियो (सीआर) का उपयोग फायदेमंद है। ऐसे अंडरले नेटवर्क में नोमा सिग्नलिंग का प्रदर्शन काफी दिलचस्प है।

साहित्य में प्रस्तुत सीडीआरटी-नोमा और सी-नोमा तकनीकें दोनों उपयोगकर्ताओं को एक साथ संकेत देकर निकट-उपयोगकर्ता (एनयू) की कीमत पर दूर के दूर-उपयोगकर्ता (एफयू) पर प्रदर्शन में सुधार करने का प्रयास करती हैं। वृद्धिशील सिग्नलिंग तकनीकों के उपयोग के बिना, सीडीआरटी- नोमा के साथ एफयू द्वारा दो की विविधता हासिल की जा सकती है, लेकिन एनयू द्वारा नहीं। इस थीसिस में, हम एनयू के प्रदर्शन को भी बेहतर बनाने का प्रयास करते हैं। यह इसे दूर स्थित एफयू की सहायता के लिए नोमा सिग्नलिंग में भाग लेने के लिए प्रेरित करता है। हालाँकि ध्यान दें कि एनयू प्रतीकों को आवंटित शक्ति को वैकल्पिक रूप से कम किया जा सकता है, और एफयू को बढ़ाया जा सकता है (जिससे एफयू प्रदर्शन में वृद्धि होगी)। इस थीसिस में, हम लगातार हस्तक्षेप रद्दीकरण (एसआईसी) के साथ संयोजन के लिए एक तकनीक विकसित करते हैं ताकि एनयू को दो की विविधता प्राप्त करने और प्रदर्शन का विश्लेषण करने की अनुमति मिल सके। सुझाई गई योजना का प्रदर्शन एसई और ऊर्जा दक्षता (ईई) दोनों के संदर्भ में उल्लेखनीय रूप से बेहतर दिखाया गया है। अंडरले सीडीआरटी- नोमा नेटवर्क के प्रदर्शन का विश्लेषण भी प्रस्तुत किया गया है। आगे यह दिखाया गया है कि वृद्धिशील सिग्नलिंग के उपयोग से एसई और ईई दोनों में और सुधार हो सकता है। प्रदर्शन पर महत्वपूर्ण जानकारी प्राप्त होती है।

सीआर एक और आशाजनक तकनीक है जो स्पेक्ट्रम साझाकरण की अनुमति देकर सीमित रेडियो संसाधनों की समस्या को दूर करने का प्रयास करती है। सीआर के अंडरले प्रकार में जिसने सबसे अधिक

आशाजनक प्रदर्शन किया है, संचारित शक्तियां हस्तक्षेप तापमान सीमा (आईटीएल) द्वारा बाधित होती हैं, और बिजली नियंत्रण के चरम हस्तक्षेप प्रकार के कारण यादृच्छिक होती हैं। इसलिए ऐसे परिदृश्यों में नोमा का प्रदर्शन खराब हो सकता है। इस थीसिस में यह दिखाया गया है कि उपयोगकर्ता चयन के साथ-साथ नोमा और ओमा के बीच स्विच करके नेटवर्क अनुकूलन, बिजली की कमी के बावजूद अच्छा प्रदर्शन प्राप्त करने की कुंजी है। यह दिखाया गया है कि चैनल राज्य सूचना (सीएसआई) पर निर्भर आईटीएल के माध्यम से प्राथमिक चैनल के सीमित ज्ञान का लाभ उठाकर, स्थिर आईटीएल के मामले में थ्रूपुट में बहुत महत्वपूर्ण लाभ प्राप्त किया जा सकता है। प्रदर्शन को अधिकतम करने के लिए इष्टतम मापदंडों के चयन में अंतर्दृष्टि के साथ, बिजली आवंटन के लिए बंद-फ़ॉर्म अभिव्यक्तियाँ प्रस्तुत की जाती हैं।

मल्टीपल एक्सेस नेटवर्क में, इस थीसिस में यह दिखाया गया है कि चैनलों की लुप्त होती प्रकृति के कारण, ओमा, नोमा और सी- नोमा के बीच मोड स्विचिंग द्वारा नेटवर्क अनुकूलन अच्छा प्रदर्शन प्राप्त करने की कुंजी है। यह आगे दिखाया गया है कि जब मोड स्विचिंग के साथ एक सरल उपयोगकर्ता चयन योजना का उपयोग किया जाता है, तो दूर के उपयोगकर्ताओं पर बहुत अच्छा प्रदर्शन प्राप्त किया जा सकता है। सांख्यिकीय निश्चित बिजली आवंटन (एफपीए) योजना में, यह दिखाया गया है कि थ्रूपुट प्रदर्शन को अधिकतम करने के लिए अकेले चैनलों के सांख्यिकीय गुणों के आधार पर बिजली आवंटन कैसे चुना जा सकता है। फिर यह दिखाया गया है कि जब चैनल ज्ञान उपलब्ध होता है, तो इसका उपयोग बुद्धिमान उपयोगकर्ता चयन और मोड स्विचिंग के साथ प्रदर्शन को और बेहतर बनाने के लिए नोमा पावर आवंटन निर्धारित करने के लिए किया जा सकता है। इस चैनल-जागरूक योजना को गतिशील बिजली आवंटन (डीपीए) योजना के रूप में जाना जाता है। आगे यह दिखाया गया है कि डीपीए योजना से ऊर्जा बचत हो सकती है। आउटेज संभावना, थ्रूपुट और ईई के लिए बंद-फ़ॉर्म अभिव्यक्तियाँ एफपीए और डीपीए दोनों योजनाओं के लिए प्राप्त की जाती हैं। यह थीसिस दर्शाती है कि द्वितीयक ट्रांसमीटर की संचारण शक्ति पर सख्त बाधाओं के बावजूद, बुद्धिमान उपयोगकर्ता चयन और स्विचिंग रणनीतियों का उपयोग करके अंडरले सीआरएन में उच्च थ्रूपुट प्राप्त किया जा सकता है। इसके अलावा, यह थीसिस प्रदर्शन लक्ष्यों को प्राप्त करने के लिए बुद्धिमान चैनल-जागरूक तकनीकों के महत्व पर जोर देती है।

डाउनलैंक मल्टीयूजर नोमा नेटवर्क में, इस थीसिस में यह दिखाया गया है कि स्रोत पर चैनल ज्ञान का दोहन करने से एसई के साथ-साथ ईई में भी नाटकीय सुधार हो सकता है। एक इष्टतम उपयोगकर्ता उपसमूह चयन तंत्र विकसित किया गया है। इष्टतम नोमा बिजली आवंटन पैरामीटर चैनल ज्ञान का उपयोग करके बंद-रूप में व्यक्त किए जाते हैं, और थ्रूपुट प्रदर्शन का विश्लेषण किया जाता है। यह दिखाया गया है कि ईई को अधिकतम करने के लिए इस ज्ञान के आधार पर संचारित शक्ति को कैसे इष्टतम ढंग से चुना जा सकता है।

यह थीसिस नोमा सिग्नलिंग के आधार पर सहकारी और संज्ञानात्मक संचार प्रणालियों के विश्लेषण और अनुकूलन में महत्वपूर्ण योगदान देती है। बढ़ते उपयोगकर्ता घनत्व और उन्नत एसई और ईई की आवश्यकता के कारण, प्राप्त अंतर्दृष्टि सिस्टम डिजाइनरों के लिए बेहद मूल्यवान है।

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ACRONYMS/ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AF	Amplify-and-Forward
ATSC	Advanced Television Systems Committee
AWGN	Additive White Gaussian Noise
B5G	Beyond Fifth Generation
bpcu	Bits Per Channel Use
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CDRT	Coordinated Direct and Relay Transmission
CI	Channel State Information Dependent Interference Temperature Limit
C-NOMA	Cooperative Non-orthogonal Multiple Access
CNM	Cooperative Non-orthogonal Multiple Access Mode
C-OMA	Cooperative orthogonal Multiple Access
CR	Cognitive Radio
CR-NOMA	Cognitive Radio Non-orthogonal Multiple Access
CRN	Cognitive Radio Network
CR-RNOMA	Cognitive Radio Relayed Non-orthogonal Multiple Access
CSI	Channel State Information
DF	Decode-and-Forward
DPA	Dynamic Power Allocation
EE	Energy Efficiency

ETSI	European Telecommunications Standards Institute
FD	Full-Duplex
FDMA	Frequency Division Multiple Access
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 of Technology
IoT	Internet of Things
IR	Incremental Relaying
ITL	Interference Temperature Limit
ITU	International Telecommunication Union
Kbps	Kilobits Per Second
LDM	Layered Division Multiplexing
LPWA	Low Powered Wide Area
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
NC	No Combining
NFC	Near-field Communication
NM	Non-orthogonal Multiple Access Mode

NOMA	Non-orthogonal Multiple Access
NR	New Radio
NU	Near User
OFDMA	Orthogonal Frequency Division Multiple Access
OM	Orthogonal Multiple Access Mode
OMA	Orthogonal Multiple Access
PDF	Probability Density Function
PN	Primary Network
PT	Primary Transmitter
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
R-NOMA	Relayed Non-orthogonal Multiple Access
RV	Random Variable
SC	Superposition coding
SDF	Selective Decode-and-Forward
SDMA	Spatial Division Multiple Access
SDR	Software-defined Radio
SE	Spectral Efficiency
SI	Static Interference Temperature Limit
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference-Plus-Noise-Ratio
SN	Secondary Network
SNR	Signal-to-Noise-Ratio
TDMA	Time Division Multiple Access
TSDSI	Telecommunications Standards Development Society, India
VoIP	Voice over Internet Protocol
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

NOTATION

$ \cdot $	Absolute value
η_E	Energy Efficiency
$\gamma(\cdot, \cdot)$	Lower incomplete Gamma function, where $\gamma(a, x) = \int_0^x t^{a-1} \exp(-t) dt$
$\gamma(a, x; b)$	Generalized incomplete lower Gamma function, where $\gamma(a, x; b) = \int_0^x t^{a-1} e^{-t-bt^{-1}} dt$
$\Gamma(\cdot)$	Gamma function, where $\Gamma(a) = \int_0^\infty t^{a-1} e^{-t} dt$
$\Gamma(\cdot, \cdot)$	Upper incomplete Gamma function, where $\Gamma(a, x) = \int_x^\infty t^{a-1} \exp(-t) dt$
$\Gamma(a, x; b)$	Generalized incomplete upper Gamma function, where $\Gamma(a, x; b) = \int_x^\infty t^{a-1} e^{-t-bt^{-1}} dt$
γ_F	Threshold SNR to decode the symbols of FU
γ_N	Threshold SNR to decode the symbols of NU
γ_P	Threshold SNR to decode the symbols of PU
Γ_{FF}	SINR at the FU to decode its own symbol
Γ_{NF}	SINR at the NU to decode FUs symbol
Γ_{NN}	SINR at the NU to decode its own symbol
Γ_{RF}	SINR at the relay to decode FUs symbol
Γ_{RN}	SINR at the relay to decode NUs symbol
σ^2	Noise variance
τ	Throughput
I	The first phase signalling
II	The second phase signalling
$\mathcal{CN}(0, a)$	Zero mean complex Gaussian distribution with variance a
D_F	Diversity order at FU
D_F^{AF}	Diversity order at FU for AF
D_N	Diversity order at NU
D_N^{AF}	Diversity order at NU for AF
D_N^{DF}	Diversity order at NU for DF
$\mathbb{E}$	Expectation operator
$E_n[\cdot]$	Generalized exponential integral for real non-zero values of order n , where $E_n[x] = \int_1^\infty t^{-n} e^{-xt} dt$ ($n = 0, 1, 2, \dots$)
E_R	Energy used at the relay
E_S	Energy used at the source
E_T	Total Energy used
$\exp[\cdot]$	Exponential function
f_F	Feedback bit from FU
f_N	Feedback bit from NU
F_τ	Proportional throughput fairness
$f_X(x)$	Probability density function of random variable X

$F_X(x)$	Cumulative distribution function of random variable X
$\bar{F}_X(x)$	Complementary cumulative distribution function of random variable X
$F_{X Y}(x)$	Cumulative distribution function of random variable X given Y
g_{ab}	Interference channel between node a and b
h_{ab}	Channel between node a and b
$K_n[\cdot]$	n^{th} order modified Bessel's function of second kind, where $K_n[x] = \frac{1}{2} \left(\frac{x}{2}\right)^n \int_0^\infty t^{n-1} e^{-\frac{1}{t} - \left(\frac{x}{2}\right)^2 t} dt$
$\mathcal{L}$	Path loss exponent
$\max(\cdot)$	Maximum operator
$\min(\cdot)$	Minimum operator
N_r	Number of receive antennas
N_t	Number of transmit antennas
N_Q	Number of qualified NUs for FPA scheme
N_Q^{CSI}	Number of qualified NUs for DPA scheme
P_N	Transmit power at the NU
P_R	Transmit power at the relay
P_S	Transmit power at the source
p_F^{AF}	FUs outage probability for AF
p_F^{DF}	FUs outage probability for DF
p_{F-CI}	FUs outage probability for CI scheme
${}_p\mathcal{F}_q(\cdot)$	Generalized hypergeometric function
p_{F-SI}	FUs outage probability for SI scheme
p_N^{AF}	NUs outage probability for AF
p_N^{DF}	NUs outage probability for DF
p_{N-CI}	NUs outage probability for CI scheme
p_{N-SI}	NUs outage probability for SI scheme
$p_P^{o,d}$	Desired primary outage
R_F	Target information rate of the FU
R_N	Target information rate of the NU
R_P	Target information rate of the PU
s_F	Transmit signal intended for FU
s_N	Transmit signal intended for NU
$\mathcal{S}_Q$	Set of qualified NUs
s_R	Superimposed signal transmitted from the relay
s_S	Superimposed signal transmitted from the source
τ_F^{AF}	Throughput at FU for AF
τ_F^{DF}	Throughput at FU for DF
τ_{F-CI}	Throughput at FU for CI scheme
τ_{F-SI}	Throughput at FU for SI scheme
τ_N^{AF}	Throughput at NU for AF
τ_N^{DF}	Throughput at NU for DF
τ_{N-CI}	Throughput at NU for CI scheme
τ_{N-SI}	Throughput at NU for SI scheme
$U(\cdot)$	Unit step function
y_F	Received signal at FU
y_N	Received signal at NU
y_R	Received signal at the relay