

Optimal Throughput for Multicast over MANET-Satellite Networks

Do Duy Tan*, Dang Phuoc Hai Trang, Truong Quang Phuc, Nguyen Van Thanh Loc,
Nguyen Van Phuc, Le Minh Thanh

Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology and Education, Vietnam

*Corresponding author. Email: tandd@hcmute.edu.vn

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ABSTRACT

The convergence of MANET and satellite networks has been considered as one of the potential solutions to provide emergency communication and disaster relief services. However, unreliable MANET and satellite links may influence seriously to data transmission. In this paper, we study the application of packet-level coding for enhancing network throughput for multicast services over integrated MANET-satellite networks. First, we characterize the performance of multicast networks in terms of the probability of packet delivery under different packet-level codes. We then formulate and solve the coding optimization problem for typical values of computational resources at the network nodes given some target probability of successful delivery to the receivers. Finally, several simulation results show significant gains in the average achievable rate at the receivers with respect to routing for representative scenarios with different types of network devices given a strictly-high probability of successful delivery of the multicast networks. Furthermore, the devices with higher computational resources can obtain significantly better throughput gain.

KEYWORDS

MANET;
Satellite;
Multicast;
Throughput;
Simulation.

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1. Introduction

We consider a network architecture where Mobile Ad-hoc Networks (MANETs) are assisted by a satellite since an emergency scenario disconnects MANETs from local terrestrial cellular networks. The MANET devices represent e.g., relief teams in an emergency situation [1–3]. In this context, our key concern is the reliable down-link communication between the operational headquarter and each particular on-site relief team which can be modeled as a multicast network where a single source node transmits a sequence of packets (e.g., an image of the local disaster area) via a line of intermediate nodes to a group of M receivers, also referred to a multicast group (MG). In multicast networks, one of the key requirements is to guarantee a target quality-of-service (QoS) level e.g., the probability of successful delivery [4], to all the receivers in a same MG. In Figure 1, we illustrate a logical representation of a multicast network with 3 receivers. Furthermore, unreliable MANET and satellite links may influence seriously to data transmission. Therefore, increasing network throughput over the MANET-satellite network calls for the use of packet-level coding i.e., network coding (NC) [5–8] which allows to guarantee reliable multicast data exchange between network devices. It is noted that when NC is employed as a solution to enhance network throughput, the computational complexity issue needs to be considered in a centralized viewpoint.

There are already related works investigating reliable communications for emergency scenarios [9, 10]. However, different from the existing works, we investigate the connectivity of separate MANETs with the support of a satellite. In addition, the performance of multicast networks with network codes has been studied in the literature [4, 11, 12]. Yet, we study the performance of different NC schemes over multicast networks with a line of intermediate nodes. The main contributions of this paper can be summarized as follows. First, for multicast networks, we formulate, solve and analyze the finite-length NC optimization problem for typical values of computational resources at the network nodes given some target probability of successful delivery to the receivers. Then, by means of simulation, we show that

our proposed method obtains significant gains in terms of the average achievable rate of the MG with respect to routing for some representative scenarios.

2. System model

The logical model of a set of MANETs, is sketched in Figure 1. OSPF would be used for the communication from MANETs to/from satellite links and AODV would be used inside a MANET [13]. Hence, every optimized path between a source and a MG is considered as a (multi-hop) multicast network including a line of intermediate nodes and several receivers. Practically, only a very limited number of MANET devices are able to directly communicate with satellite due to high cost of data transmission over satellite as well as hardware cost. Therefore, we assume that the satellite transmits to an arbitrarily intermediate node/device instead of directly transmitting to the decoder. We note that the case that the satellite can transmit directly to the decoder without the need of multi-hop communication is the best case and can be considered as a sub-case of our illustrative network model.

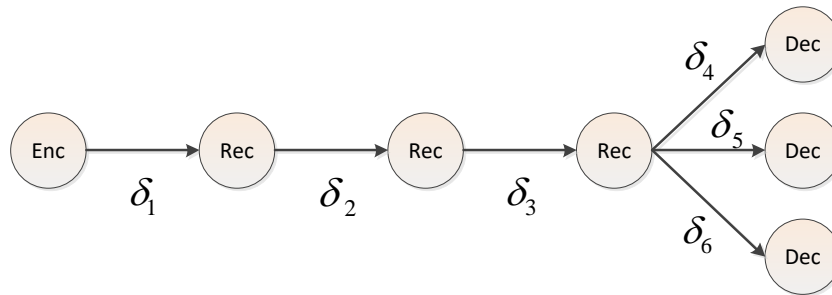


Figure 1. Logical representation of a multicast network with 1 source (encoder), 3 intermediate nodes (re-encoders), and $M = 3$ receivers (decoders).

We focus on a particular multicast information flow as a sequence of transmitted packets along a multicast network G of N nodes and L links including a source node, M receivers, and $I = N - M - 1$ intermediate nodes. We denote D as the corresponding vector of per-link erasure rates. Let us denote δ_i as the i -th link erasure rate in G where $1 \leq i \leq I$ is the index of links connecting the source and the line of intermediate nodes and $I+1 \leq i \leq L$ is the index of links connecting the last intermediate node and M receivers.

A packet stream is produced at the source. For a finite field \mathbb{F}_q ($q = 2^m$), we use S symbols as the information packet length. A generation is defined as a group of K information packets, denoted as $\in \mathbb{F}_q^{S \times K}$. We assume per-generation block coding with block-length N and $\rho = \frac{K}{N}$ is the coding rate. $Pe^j(\rho)$ is the packet loss rate (PLR) after decoding at the j -th receiver ($1 \leq j \leq M$). The probability of successful delivery of a M -user multicast network G is defined as the probability that all the receivers of the same MG are able to recover the overall information packets and is given as [4]

$$\phi(\rho) = \prod_{j=1}^M (1 - Pe^j(\rho)) \quad (1)$$

We denote ϕ_0 as the target probability of successful delivery at the receivers. We consider this as the target QoS level of a M -user multicast network. Achievable rate at the j -th receiver in G with NC and with routing (i.e., without NC) ($1 \leq j \leq M$) is defined as $R_{NC}^j(\rho) = \rho (1 - Pe^j(\rho))$ and $R_R^j = \prod_{i=1}^I (1 - \delta_i)(1 - \delta_{I+j})$, respectively. Average achievable rate of the MG in G with NC and with routing is defined as $R_{NC}^{av}(\rho) = \frac{\sum_{j=1}^M R_{NC}^j(\rho)}{M}$ and $R_R^{av} = \frac{\sum_{j=1}^M R_R^j}{M}$, respectively. The required computational resources is the amount of computational resources needed for coding operations at the n -th node in G ($1 \leq n \leq N$) denoted by $\beta^n(\rho)$. Constraint on computational resources of the n -th node and the vector of per-node computational resources is denoted by β_0^n and B , respectively.

3. Network coding scheme and computational resources

In this paper, we study the performance of multicast networks under random linear network codes. We consider random linear scheme (RLNC), systematic random linear scheme (SNC), and SNC with packet scheduling (SNC-S). For each network code, we model the encoding, re-encoding, and decoding functions in matrix notation and derive the theoretical expression of PLR after decoding at the j -th receiver, $Pe^j(\rho)$ ($1 \leq j \leq M$). The PLR for RLNC and SNC is derived in [14] while the PLR for SNC-S can be easily deduced from the PLR for SNC [15].

We consider the computational resources for coding operations in terms of the total number of logic gates required for implementing multiplication and addition operations over $GF(2^m)$ which can be approximated by m -bit arithmetic operations as $2m^2 + 2m$ and m logic gates, respectively [16]. The required computational resources for SNC/SNC-S encoding in terms of logic gates can be obtained as $\beta_{enc}(\rho) = N_{enc}^M(2m^2 + 2m) + N_{enc}^A m$, where $N_{enc}^M = KNS = \frac{K^2 S}{\rho}$ and $N_{enc}^A = (K - 1)NS = \frac{K(K-1)S}{\rho}$ are the number of multiplications and additions, respectively. The required computational resources for decoding based on Gauss-Jordan elimination algorithm is given as $n\beta_{dec}^n(\rho) = N_{dec}^M(2m^2 + 2m) + N_{dec}^A m$, where N_{dec}^M and N_{dec}^A are given in [17].

In general, the required computational resources at are-encoder is upper bounded as $\beta_{rec}^n(\rho) \leq \beta_{dec}^n(\rho) + \beta_{enc}(\rho)$ ($1 < n \leq N-M$). Computational resources required at the source and the j -th receiver in G are given as $\beta^1(\rho) = \beta_{enc}(\rho)$ and $\beta^n(\rho) = \beta_{dec}^j(\rho)$ ($1 \leq j \leq M, N-M+j \leq n \leq N$), respectively. We observe that computation-limited nodes will not be able to process NC schemes requiring low coding rates. Therefore, we assume representative values for the available computational resources at nodes e.g., $\beta_0^{phone} = 100 \cdot 10^6$, $\beta_0^{lap} = 200 \cdot 10^6$ and $\beta_0^{server} = 500 \cdot 10^6$ logic gates, according to different platforms such as smartphones, laptops, and servers, respectively [5].

4. Coding rate optimization

In this paper, we aim at identifying the optimal finite-length coding rate, ρ^* , that maximizes the average achievable rate at the M receivers in G , $R_{NC}^{av}(\rho)$, while satisfying the target delivery probability, ϕ_0 , given the vector of available computational resources at all the nodes, B . The optimal coding rate ρ^* and optimal block-length N^* are identified by the following optimization problem

$$\begin{aligned}
 (\rho^*, N^*) &= \underset{\rho, N}{\operatorname{argmax}} R_{NC}^{av}(\rho) & (2) \\
 \text{s.t. } &\phi(\rho) \geq \phi_0, \\
 &\beta^v(\rho) \leq \beta_0^v
 \end{aligned}$$

with $\beta_0^v \in B, \forall v \in [1, N]$. The probability of successful delivery at the MG, $\phi(\rho)$, can be averaged via extensive simulations or calculated using theoretical expressions. The identification of the solution for Problem (2) can be facilitated as follows. First, we show that a searching algorithm is sufficient to identify an optimal coding rate given a pre-defined N, ρ_N^* . Then, we can identify the ρ^* from a set of ρ_N^* w.r.t. a range of N .

Proposition 1: *Given N and ϕ_0 , a binary searching algorithm is sufficient to identify an optimal coding rate ρ_N^* and converges in $k' = \lceil \log_2(|\Psi_N| - 1) \rceil$ iterations with Ψ_N the set of coding rates available for searching.*

Proof: We have that for a particular N , the PLR at the j -th receiver w.r.t. a NC scheme, $Pe^j(\rho)$, is a non-decreasing function of coding rate [6,14]. Hence, $\phi(\rho)$, the product of $1 - Pe^j(\rho) \forall j \in [1, M]$, is a non-increasing function of coding rate. Moreover, for low PLR, the achievable rate at a specific receiver is an increasing function with coding rate. Hence, assume $K = \lceil N\rho \rceil$, a unique ρ_N^* can be identified by a binary searching algorithm so that $\phi(\rho) \geq \phi_0$ holds. Moreover, it is easy to prove that the searching algorithm converges in $k' = \lceil \log_2(|\Psi_N| - 1) \rceil$ iterations [18]. Due to space limitations, we do not give the detailed proof here.

Proposition 1 shows that given N the optimal coding rate can be identified by

$$\begin{aligned}
 (\rho_N^*|N) &= \underset{\rho}{\operatorname{argmax}} R_{NC}^{av}(\rho)|N = \max_{\rho} \rho|N \\
 \text{s.t. } \phi(\rho) &\geq \phi_0, \\
 \beta^v(\rho) &\leq \beta_0^v,
 \end{aligned} \tag{3}$$

and a binary searching algorithm [18] is sufficient to solve Problem (3).

We evaluate the performance of random linear NC schemes with $\phi_0 = 0.9999$ representing the quasi-error-free channel [19], $q = 2^8$, $\rho_0 = \frac{1}{N}$, $|\Psi_N| = N - 1$ and $\delta = 0.05$ representing 802.11 wireless links [20]. We can indicate that when the coding block-length needs to be small e.g. $N \leq 100$, the optimal coding rate (ρ_N^*) increases exponentially with N . Hence, when $\rho_N^*(N)$ increases with N , $R_{NC}^{av}(\rho_N^*(N))$ would increase accordingly. Consequently, the maximum average achievable rate corresponds the largest $\rho_N^*(N)$ given a range of N that the design constraints are guaranteed [6,14,15]. Hence,

$$(\rho^*, N^*) = (\rho_N^*|N^*, N^*) = \underset{N}{\operatorname{argmax}} \rho_N^*|N. \tag{4}$$

In overall, Problem (2) can be solved by the following procedure:

- For each $N = N_1, N_2, \dots, N_{\max}$, find the corresponding optimal coding rate, $\rho_{N_1}^*, \rho_{N_2}^*, \dots, \rho_{N_{\max}}^*$, by solving Problem (3). The solution can be identified by a binary searching algorithm [18]. We denote Ψ_{N_v} as the set of coding rates available for searching w.r.t. N_v ($v = 1, 2, \dots, \max$) (e.g., given N_1 , $\rho[i] = i\rho_0$, $1 \leq i \leq |\Psi_{N_1}|$ with set $\rho_0 = \frac{1}{N_1}$, $|\Psi_{N_1}| = N_1 - 1$). At each step, discarding the first half of the available coding rates is performed if the design constraints are satisfied. Otherwise, the algorithm removes the second half of the available coding rates.
- For the set Θ of available N , find (ρ^*, N^*) by solving Problem (4) which is also the solution to Problem (2). As showed, the maximum average achievable rate corresponds the largest $\rho_N^*(N)$ given a range of N . Hence, a binary searching algorithm can be used to identify (ρ^*, N^*) .

5. Performance evaluation

5.1. Simulation Settings

We provide simulation results in Matlab to evaluate the performance of different NC schemes in multicast networks. We consider an emergency scenario as showed in Section 1 where a satellite is employed to support the connectivity between a source and M receivers. Coding rate is optimized according to Problem (1). For each setting, the PLR for each network code is averaged over 5000 simulations. The block-length range is given according to the region of exponential coding rate increase, $10 \leq N \leq 100$.

We consider a particular multicast network G of N nodes and L links (as illustrated in Figure 1) including two satellite links and $L - 2$ communication links between MANET devices in order. The scenario herein considered refers to a MG composed by $M = 5$ receivers. We assume realistic GEO satellite transmission with links affected by light rainfall e.g., $\delta_{SAT} = 0.1$. All MANET links undergo the same erasure rate e.g., $\delta_{MANET} = 0.05$ and 0.1 representing 802.11 wireless links [20] in low and high erasure rates, respectively. Packet length is 1500 bytes with information length $S = 1400$ bytes ($m = 8$). We set $\phi_0 = 0.9999$ representing strictly-high probability of successful delivery. Moreover, we assume the same computational resource constraints for all nodes, $\beta_0^n = \beta_0$, ($\forall n \in [1, N]$). Each node has either low, moderate, or high computational resources representing different platforms as mentioned above.

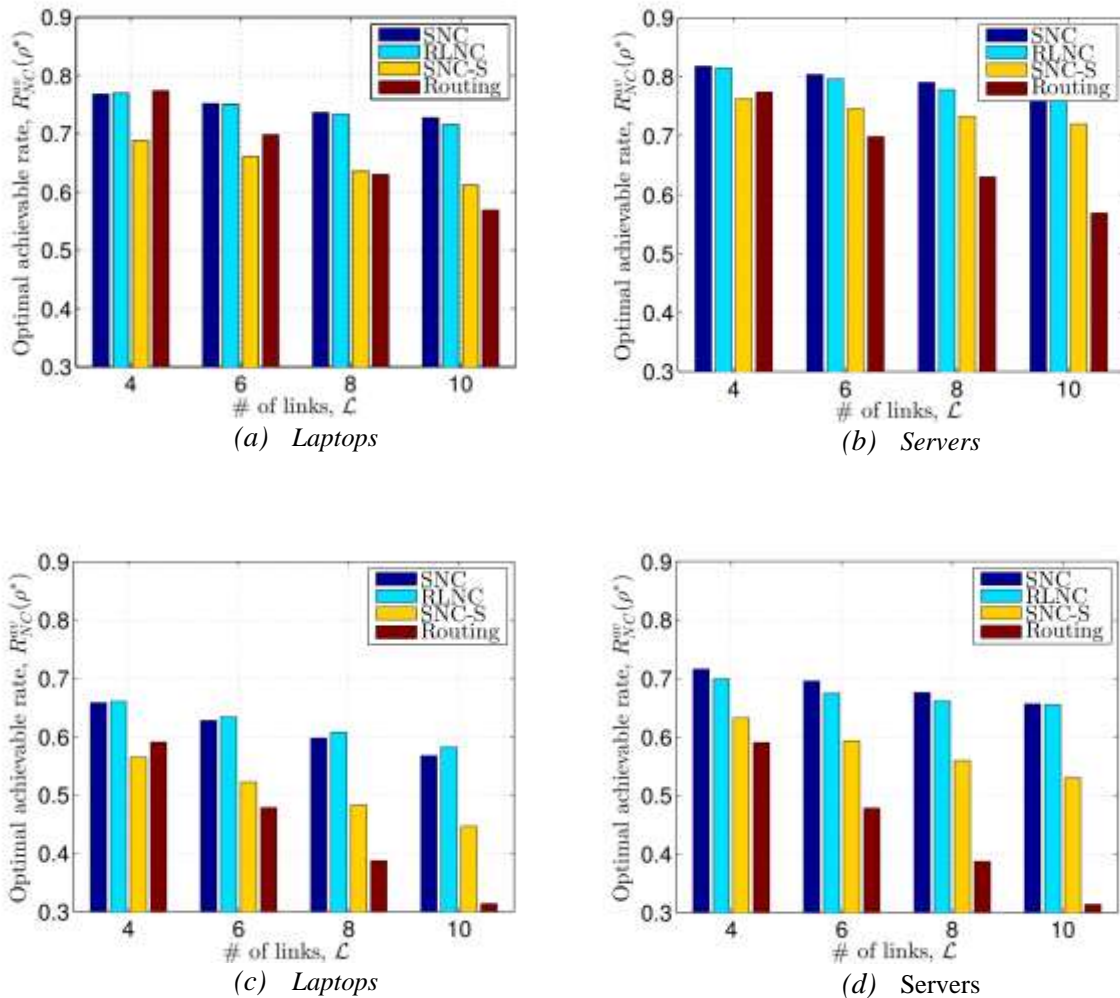


Figure 2. Average optimal achievable rate according to different NC schemes and average achievable rate with routing at the receivers in G , $R_{NC}^{av}(\rho^*)$ and R_R^{av} , respectively, versus L with different representative devices, for $\phi_o = 0.9999$ with erasure rates $\delta_{MANET} = 0.05$ (the first row) and $\delta_{MANET} = 0.1$ (the second row).

5.2. Simulation results

In Figure 2, we show the average optimal achievable rate w.r.t. different NC schemes and the average achievable rate with routing obtained at the receivers in G . For the same per-link erasure rates and representative devices, the longer the path length between source and receivers, the lower the average optimal achievable rate. This is because the PLR at each receiver is an increasing function of path length. Therefore, the lower the coding rate is needed to ensure the target probability of successful delivery. More importantly, the use of the network codes could ensure the strictly high probability of successful delivery at the receivers while routing only does not. Moreover, for the same representative devices, the higher the available computational resources, the higher the average optimal achievable rate which shows the impact of the computational resources at the nodes on the performance of the network codes. This is due to the fact that as the optimal coding rate increases with N , K increases accordingly. The higher the K , the higher the computational resources required for NC operations. Hence, the higher the available computational resources, the higher the optimal coding rate which means that the higher the average optimal achievable rate.

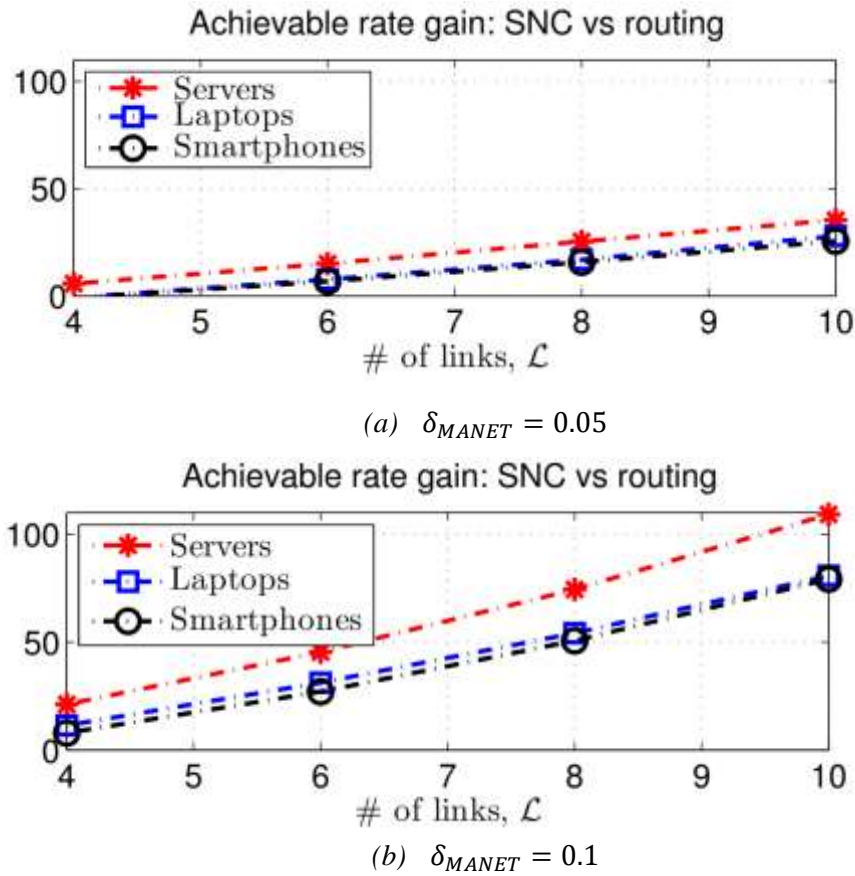


Figure 3. Optimal achievable rate gain with SNC (in %) at the receivers in G with different representative devices for $\phi_o = 0.9999$.

From the results showed in Figure 2, Figure 3 denotes the optimal achievable rate gain at the receivers in G with SNC as a function of path length for different representative devices. For each particular network code, the optimal achievable rate gain is defined as $\frac{R_{NC}^{av}(\rho^*) - R_R^{av}}{R_R^{av}}$ (in %). As expected, the optimal achievable rate gain increases with path length, available computational resources, and per-link erasure rates. For the same per-link erasure rates, the higher the path length, the higher the optimal achievable rate gain due to the higher slope of the decreasing average optimal achievable rate with routing compared to that of the considered NC schemes (see Figure 2). Furthermore, the devices with higher available computational resources can provide better optimal achievable rate gain. For instance, at $L = 10$ links, for the case of smartphones, the achievable rate gain with SNC could obtain approximately 30% and 80% according to $\delta_{MANET} = 0.05$ and $\delta_{MANET} = 0.1$ while for the case of servers, it could reach up to 40% and 110%, respectively.

6. Conclusions

In this paper, we investigated finite-length NC for reliable multicasting over combined MANET-satellite networks in emergency context. Simulation results show that packet-level coding can obtain significant gains in terms of the average achievable rate at the end receivers compared to routing for different representative types of network devices given strictly-high probability of successful delivery of the M -receiver multicast network.

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Do Duy Tan received his B.S. degree from Ho Chi Minh City University of Technology (HCMUT), Vietnam, and M.S. degree from Kumoh National Institute of Technology, Korea, in 2010 and 2013, respectively. He received his Ph.D. degree from Autonomous University of Barcelona, Spain, in 2019. He is currently with the Department of Computer and Communication Engineering, Ho Chi Minh City University of Technology and Education (HCMUTE) in Vietnam as an Assistant Professor. His main research interests include real-time optimisation for resource allocation in wireless networks and coding applications for wireless communications.



Dang Phuoc Hai Trang is a lecturer at Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam, since 2007. He received his B.Eng and M.Eng. degrees in Electronic Engineering from HCMC University of Technology and Education in 2007 and 2011, respectively. His research focuses on Internet of things, artificial intelligence, and deep learning.



Trung Quang Phuc was born in Can Tho City, Vietnam. He received the B.Eng degree in Electronics and telecommunication engineering and the M.Eng degree in Electronics engineering from the Ho Chi Minh City University of Technology and Education, Vietnam, in 2011 and 2014, respectively. Currently, He is with the Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology and Education, Vietnam as a Research Assistant and Ph.D. student. His research interests include convex optimization techniques, heterogeneous networks, Internet of Things, and Intelligent Reflecting Surfaces (IRS).



Nguyen Van Thanh Loc received his B.S degree from Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam. His main research interests include communication networks and applications of error-control coding for wireless communications.



Nguyen Van Phuc received his B.S. degree and M.S. degree from Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam in 2008 and 2011 respectively. He is currently a lecturer at Department of Computer and Communications Engineering, Ho Chi Minh City University of Technology and Education, Vietnam. His research interests include applications of communication systems, information coding and artificial intelligence.



Le Minh Thanh received his B.S. and M.S. degrees from Ho Chi Minh City University of Technology (HCMUT), Vietnam, in 2000 and 2003, respectively. He is currently working as a lecturer at the Department of Computer and Communication Engineering, Ho Chi Minh City University of Technology and Education (HCMUTE) in Vietnam. His research interests include applications of digital signal processing, microwave engineering, and communication systems.