Cooperative Communication Scheme using Network Coding and Constructive-Interference Phenomena for Information-Centric Wireless Networks

Shintaro Mori
Department of Electronics Engineering and Computer Science
Fukuoka University
8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan
e-mail: smori@fukuoka-u.ac.jp

Abstract—**This paper describes a cooperative communication scheme for information-centric wireless networks, focusing on disaster-resilient smart-city applications. The proposed scheme uses a network coding technique and constructive-interference phenomena to enhance data distribution and reduce radio interference among relay nodes. The results of computer simulations demonstrate the recoverability of forwarding data under the cross-interference environment and the improvement of caching-data spread.**

Keywords-Information-centric wireless networks; Network coding (NC); Cooperative communication.

I. Introduction

Internet-of-Things (IoT) applications have become widespread across various domains, such as smart cities, industrial automation, human healthcare, and smart everything, which has spurred an explosive growth in the number of IoT devices. Central city areas are increasingly using information and IoT technologies to resolve problems related to urbanizations, and thus, the overall IoT systems have been widely adopted as a solution for various urban characteristics, social needs, and governmental structures [1]. Smart cities are typically considered a panacea for urban problems, but large-scale natural disasters and global pandemics are significant treats to our daily lives. Therefore, ensuring the bright future of smart cities, i.e., achieving disaster-resilient smart cities, is of greater importance and influence with modern applications in diverse circumstances. Success in this context is dependent on the effective deployment of advanced wireless network technologies.

Smart-city applications are characterized by use of a massive connectivity, known as machine-type communications, which is quite different from traditional human-type communications in terms of efficiency and reliability. The features of these systems include low power, broad coverage, ultra-density, and mobile edge computing [2]. In addition, today's smart-city solutions face unique limitations due to unpredictable and non-uniform traffic, and some areas may be outside the wireless network coverage, such as rural areas or any area after a disaster has occurred [3]. In disaster-resilient smart cities, the deployment of secure and reliable wireless communications is of extreme importance when dealing with users' health records and other sensitive information [4]. For example, to enable public-safety broadcasting, mission-critical control, and emergency calls, the smart-city applications must be resilient and robust, and provide instant communication with various services [5].

One promising element of the solution for the above demands is the use of an Information-Centric Network (ICN), (e.g., a content-centric network or named-data network). This is a promising network architecture that is poised to replace the current IP-based networks [6]. It natively supports features, such as abstraction, naming, and in-network caching, improves delays and reduces network traffic. Moreover, ICN-based systems can decouple data from its original location and adopt individual data-based security at the network level. However, as far as we know, suitable wireless systems have not yet been sufficiently investigated and discussed from the viewpoints of integrating communication, caching, computing, control, sensing, and localization technologies in disaster-affected and communications outage areas [7].

As a physical-layer protocol underpinning ICN-based networks, the ad-hoc wireless networking and multi-hop relay networking techniques function as clues for adopting practical usage. These technologies enhance the domain of autonomous-distributed services at the cost of efficient utilization of system resources [8]. However, they come with several technical concerns, including limited battery power, range between devices, bandwidth, dis-connectivity, network overload, data redundancy, communication overhead, network lifetime, lack of information, and data integration difficulties. Therefore, a new ICN-based network protocol and friendly wireless communications technologies are strongly required.

On the basis of the above background, this paper provides an overall blueprint of our study in progress, including a novel cooperative communication scheme for effective ICN-based wireless networks. Cooperative communications technologies can be used to increase the gains by harnessing the effects of path diversity, i.e., by having a relay node send the same data to a destination node if the data transmission is not successful. In the proposed scheme, in order to improve the performance of such communication, we apply a Network Coding (NC) [9] technique to eliminate the amount of network traffic on relay nodes. In addition, to reduce the radio interference among multiple relay nodes during the data flooding process, the proposed scheme utilizes a constructive-interference phenomena [10].

The combination of NC and ICN has attracted significant interest in recent studies. Montpetit et al. [11] utilized them in the internetworking layer, by applying the NC technique to enhance the performance of forwarding data in ICNs. Mekbungwan et al. [12] proposed an NC-based data dissemination system made up of bulk data, such as photos, maps, and databases for situational awareness in post-disaster areas. It was designed on the basis of delay-torrent networking's store-carry-and-forward method in order to reduce the amount of network traffic on relay nodes. For the next-generation cellular networks, the packet duplication method is being introduced to meet the 99.999% reliability requirement, where the original packet and its duplicate are transmitted via two different physical paths, which is the same concept as the path-diversity technique [13]. However, the radio resource consumption is proportional to the number of data copies, and this duplication of data caching leads to a significant waste of radio resources. To tackle this problem, Zhu et al. [14] proposed a new task-oriented communication technology in which the waveform superposition property of a wireless channel is exploited to achieve over-the-air aggregation of data simultaneously transmitted by devices. The idea of overlaying signals can be seen as a kind of NC in the physical layer.

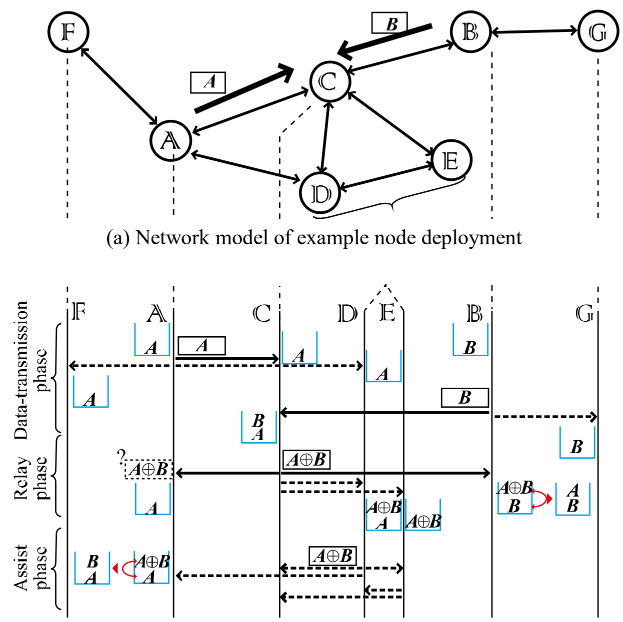
The remainder of this paper is organized as follows. In Section II, we go over the basic principle of cooperative communications. Section III describes the proposed scheme, and Section IV presents the numerical results. We conclude in Section V with a brief summary and mention of future work.

II. Cooperative Communications in Wireless Networks

Communication between source and destination takes place through different paths by means of cooperating entities called relays. Among the relay techniques in wireless (multi-hop and ad-hoc) networks, the decode-and-forward relaying method is used to decode the data that reaches the relay node and then re-encode and forward them. Another technique, the amplify-and-forward relaying method, can be selected as a simple forwarding mechanism. In the example shown in Figure 1 (a), we focus on nodes $\mathbb{A}$, $\mathbb{B}$, and $\mathbb{C}$ and presume that $\mathbb{A}$ and $\mathbb{B}$ send $\mathbb{A}$'s data of $\boldsymbol{A}$ and $\mathbb{B}$'s data of $\boldsymbol{B}$, and $\mathbb{C}$ exchanges them as relay nodes. In this case, the data transmission is completed in four steps: sending $\boldsymbol{A}$ from $\mathbb{A}$ to $\mathbb{C}$, sending $\boldsymbol{B}$ from $\mathbb{B}$ to $\mathbb{C}$, forwarding $\boldsymbol{A}$ from $\mathbb{C}$ to $\mathbb{B}$, and forwarding $\boldsymbol{B}$ from $\mathbb{C}$ to $\mathbb{A}$. The NC technique is used here with the aim of improving throughput. When $\mathbb{C}$ transfers the bit-by-bit mixed data of $\boldsymbol{A}$ and $\boldsymbol{B}$ by utilizing an Exclusive OR (XOR) operation, the data transmission procedure can be reduced to three steps: sending $\boldsymbol{A}$ from $\mathbb{A}$ to $\mathbb{C}$, sending $\boldsymbol{B}$ from $\mathbb{B}$ to $\mathbb{C}$, and forwarding $\boldsymbol{A} \oplus \boldsymbol{B}$ from $\mathbb{C}$ to $\mathbb{A}$ and $\mathbb{B}$ during broadcasting. After receiving $\boldsymbol{A} \oplus \boldsymbol{B}$, $\mathbb{A}$ can restore $\boldsymbol{B}$ by $(\boldsymbol{A} \oplus \boldsymbol{B}) \oplus \boldsymbol{A}$, and $\mathbb{B}$ can restore $\boldsymbol{A}$ in the same manner. Note that $\oplus$ denotes the XOR operator.

III. Proposed Scheme

ICN decouples the data from its original location using a name-based data-centric network scheme, which enables the network layer to cache and deliver named data regardless of the availability of the original (source) publisher. Moreover, ICN can provide content-based security, i.e., all security-sensitive information can be exchanged via the wireless channel. In this section, we provide an overview of the proposed scheme, including the proposed cooperative scheme, Media Access Control (MAC) protocol, and wireless communications protocol.



(a) Network model of example node deployment

(b) Message and data flow of proposed data-forwarding processing

Figure 1. Proposed cooperative communication scheme

A. Proposed cooperative communications

In-network caching—where each node duplicates the frequently used data by leveraging their embedded cache memory—helps to decrease the end-to-end delay and reduce the network traffic. To accelerate the effect of the caching processing, the nodes should actively accumulate the caching data. One of the key features of a wireless communication system is that it is generally able to overhear what neighbor nodes can receive whether they desire it or not. For example, in Figures 1 (a), when $\mathbb{A}$ sends $\boldsymbol{A}$ to $\mathbb{C}$, $\mathbb{F}$ and $\mathbb{D}$ can also receive $\boldsymbol{A}$; similarly, when $\mathbb{B}$ sends $\boldsymbol{B}$ to $\mathbb{C}$, $\mathbb{G}$ can also receive $\boldsymbol{B}$, which is essentially an off-path caching mechanism. Similarly, $\boldsymbol{A} \oplus \boldsymbol{B}$ from $\mathbb{C}$ can be received not only from $\mathbb{A}$ and $\mathbb{B}$ but also from $\mathbb{D}$ and $\mathbb{E}$.

For the NC-encoded data, in the proposed scheme, $\mathbb{D}$ and $\mathbb{E}$ also send $\boldsymbol{A} \oplus \boldsymbol{B}$ as a helper with $\mathbb{C}$ by performing multiplexing in the assist phase, as shown in Figure 1 (b). As a result, if $\mathbb{A}$ fails to receive $\boldsymbol{A} \oplus \boldsymbol{B}$ from $\mathbb{C}$, it can recover it by utilizing $\boldsymbol{A} \oplus \boldsymbol{B}$ from $\mathbb{D}$ thanks to the benefit of path diversity afforded through the different wireless channels. By using this mechanism, the nodes located around $\mathbb{D}$ and $\mathbb{E}$ but outside the coverage area of $\mathbb{C}$ can be additionally off-path cached, which expands the number of new cashable nodes.

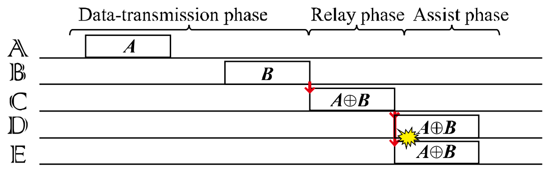


Figure 2. Baseline scenario of proposed scheme in MAC layer

B. Proposed MAC protocol

The pure (unslotted) Aloha method has been adopted as a channel access protocol in commercial low-power wide-area networks, such as SigFox and long-range alliance. In these systems, to eliminate automatic repeat-request messages, the data are iteratively transmitted. The motivation behind using an uncomplicated protocol is to simplify the device implementation (including low-energy consumption), and because the synchronization among nodes is not practically available.

For the above scenario, the proposed scheme is similarly based on current systems. To support the cooperative mechanism, each node has four states: standby, transmission, relay, and assist. Every node regularly maintains the standby state (e.g., 𝔽 and 𝔾), and the status is changed to the transmission state when it makes a data transmission request (e.g., 𝔸 and 𝔹). While receiving surrounding (overheard) data, if the node receives two different data and those data should be forwarded, the status moves to the relay state (e.g., ℂ). On the other hand, if the received data is NC-encoded data, the status switches to the assist state (e.g., 𝔻 and 𝔼). We assume that every node knows whether it needs to relay the data, that the NC-encoded data's number of multi-hops is predefined, and that the nodes can determine their upper limitation of forwarding in order to avoid unlimited hops.

The current wireless communication systems using the pure-Aloha method presuppose that the data transmission has a sufficiently long interval, implying that collision or interference among nodes will not be fatal issues. However, as shown in Figure 2, in the proposed scheme, since the relay nodes and assist nodes forward the NC-encoded data immediately (in the relay and assist phases), collision and interference in a regional area are inevitable.

C. Proposed physical protocol

To tackle the issue of collision and interference caused by forwarding multiple NC-encoded based packets, the proposed scheme adopts the constructive-interference phenomena—if receiver-side nodes can detect a superposition of baseband signals from multiple transmitter-side nodes, the interference can be ignored. In wireless sensor networks, constructive interference has not been extensively exploited because of the difficulty of achieving sufficiently accurate synchronization and the requirement of highly predictable software delays. However, this approach is suitable for the scenarios in which the proposed scheme is applicable (i.e., in the relay and assist phases). Note that, in cases where different data are in conflicts with each other, the proposed scheme cannot be applied, which is beyond the scope of our present study.

TABLE I. SIMULATION PARAMETERS

Terms	Values
Frame length	1,000 bit
Error-control coding	N/A
Modulation method	Binay phase shift keying with Gray mapping rule
Detector's decision type	Hard-decision
Carrier-signal filter	Raised cosine (square root) Rolloff factor: 0.22, Span: 12 symbol
Sampling rate of waveform	4 samples/symbol
Channel model	Additive white Gaussian noise
Signal-to-noise ratio	Relay node: 20 dB, Assist node: 20 dB

IV. NUMERICAL RESULT

In our initial evaluation of the proposed scheme, we investigated the restorability of the baseband signal by using the constructive-interference phenomena and the improvement in data caching among nodes.

Assuming an experimental network composed of a relay node, an assist node, and a receiver node, we implemented a scenario in which the relay node and the assist node send the same data packet to the receiver node. In other words, it is the same as the case where ℂ and 𝔻 forward the NC-encoded data and 𝔸 receives them (Figure 1). The computer simulation is conducted using the Matlab simulator and the simulation parameters are listed in Table I. The waveforms of the radio signal arriving from the relay and assist nodes are generated using the same data and system, but they have a time gap of φ. Figure 3 shows the detector's performance for the received signal. Let T denotes the time period required to transmit one symbol of the modulation method. Due to space limitations, we do not illustrate the cases where φ = 0 and φ = T but the former had a clearly separated constellation of received signals and a clear eye pattern, while the latter had the opposite result and thus the detector could not demodulate. According to the results in Figure 3, when φ = 1/4T, 2/4T, and 3/4T, we could achieve the separate construction and obtain a clear eye pattern, and the receiver node could correctly decode.

To illustrate the benefit of the proposed assist nodes, we performed another evaluation using computer simulation implemented in C++ language. In this simulation, 10,000 nodes were deployed in a 1-km^2 area, the communication range of the nodes was set to 100 m, and the unreachable probability of the data (i.e., packet error ratio) was set to 5%. In the conventional scheme, the relay node forwards the NC-encoded data three times, whereas, in the proposed scheme, the assist nodes that receive the NC-encoded data forward at the same time as the relay node. Since the assist nodes that receive the first-forwarded data from the relay station will transmit them twice, and the nodes that receive the second-forwarded data will transmit them once, the end of the assist phase can keep in step with the end of the relay phase, and the proposed scheme can prevent infinite data flooding. As we can see in Figure 4 (a), the number of successfully cached nodes per 10,000 was improved by 43.5% thanks to the assist nodes. As for spreading the NC-encoded data, as shown in

 ISBN: 978-1-61208-940-9

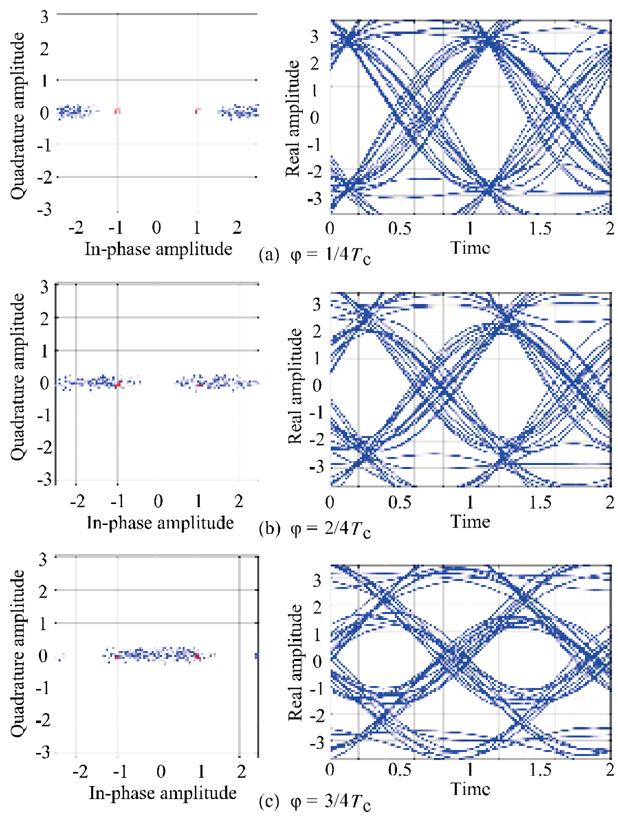


Figure 3. Receiver-side detector's performance, including constellation diagram and eye diagram, for received signals with a time lag.

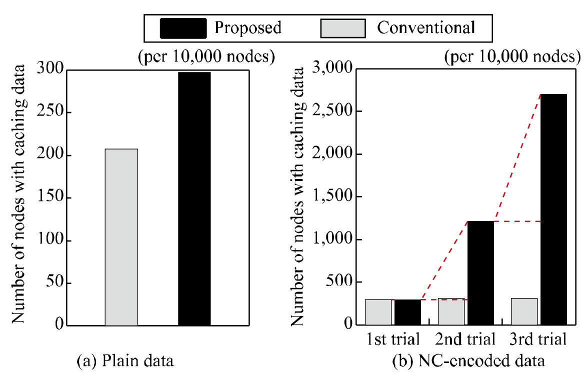


Figure 4. Number of nodes that successfully received and cached

Figure 4 (b), when the forwarding trials were increased, the nodes were enhanced by 306% and 123% for the proposed scheme compared to just 4.98% and 0.234% for the conventional scheme. At the end of the relay and assist phases, the proposed scheme could cache 8.61 times as many nodes as the conventional one. Note that, for decoding the NC-encoded data, plain data is required, e.g., either $\boldsymbol{A}$ or $\boldsymbol{B}$ for $\boldsymbol{A} \oplus \boldsymbol{B}$.

V. CONCLUSION

This paper proposed a novel cooperative communication scheme using the NC technique with constructive-interference phenomena for information-centric wireless networks. Numerical results of our initial evaluation of the scheme were reported. As future work, we will expand the practical scenarios from the quality-of-service perspective to investigate long-lifetime and robustness characteristics.

ACKNOWLEDGMENT

A part of this work was supported by JSPS KAKENHI Grant Number JP21H03436.

REFERENCES

[1] N. Chen, T. Qiu, L. Zhao, X. Zhou, and H. Ning, "Edge intelligent networking optimization for Internet of things in smart city," *IEEE Wireless Commun.*, vol. 28, no. 2, pp. 26–31, Apr. 2021.

[2] F. Guo et al., "Enabling massive IoT toward 6G: A comprehensive survey," *IEEE Internet of Things J.*, vol. 8, no. 15, pp. 11891–11915, Aug. 2021.

[3] M. El-Tanab and W. Hamouda, "An overview of uplink access techniques in machine-type communications," *IEEE Network*, vol. 35, no. 3, pp. 246–251, May/June 2021.

[4] Y. Li, Y. Yu, W. Susilo, Z. Hong, and M. Guizani, "Security and privacy for edge intelligence in 5G and beyond networks: Challenges and solutions," *IEEE Wireless Commun.*, vol. 28, no. 2, pp. 63–69, Apr. 2021.

[5] Y. Boujelben, "Scalable and QoS-aware resource allocation to heterogeneous traffic flows in 5G," *IEEE Internet of Things J.*, vol. 8, no. 20, pp. 15568–15581, Oct. 2021.

[6] O. Serhane, K. Yahyaoui, B. Nour, and H. Moungla, "A survey of ICN: Content naming and in-network caching in 5G and beyond networks," *IEEE Internet of Things J.*, vol. 8, no. 6, pp. 4081–4104, Mar. 2021.

[7] B. Ji et al., "Several key technologies for 6G: Challenges and opportunities," *IEEE Commun. Std. Mag.*, vol. 5, no. 2, pp. 44–51, June 2021.

[8] O. Hayat, Z. Kaleem, M. Zafarullah, R. Ngah, and S. Z. M. Hashim, "Signaling overhead reduction techniques in device-to-device communications: Paradigm for 5G and beyond," *IEEE Access*, vol. 9, pp. 11037–11050, 2021.

[9] D. Umehara, T. Hirano, S. Denno, M. Morikura, and T. Sugiyama, "Wireless network coding in slotted aloha with two-hop unbalanced traffic," *IEEE J. Sel. Areas in Commun.*, vol. 27, no. 5, pp. 647–661, June 2009.

[10] F. Ferrari, M. Zimmerling, L. Thiele, and O. Saukh, "Efficient network flooding and time synchronization with Glossy," *Proc. ACM/IEEE Int. Conf. Info. Process. Sensor Networks (IPSN)*, Apr. 2011, pp. 73–84.

[11] M. Montpetit, C. Westphal, and D. Trossen, "Network coding meets information-centric networking: An architectural case for information dispersion through native network coding," *Proc. ACM WS Emerging Name-Oriented Mobile Networking Design-Architecture, Algorithms, and App. (NOM)*, June 2012, pp. 31–36, doi: 10.1145/2248361.2248370.

[12] P. Mekbungwan, A. Tunpan, and K. Kanchanasut, "An NC-DTN framework for many-to-many bulk data dissemination in OLSR MANET," *Proc. Int. Wireless Commun. and Mobile Comp. Conf. (IWCMC)*, Aug. 2015, pp. 964–969, doi: 10.1109/IWCMC.2015.7289213.

[13] S. Baek, D. Kim, M. Tesanovic, and A. Agiwal, "3GPP new radio release 16: Evolution of 5G for industrial Internet of things," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 41–47, Jan. 2021.

[14] G. Zhu, J. Xu, K. Huang, and S. Cui, "Over-the-air computing for wireless data aggregation in massive IoT," *IEEE Wireless Commun.*, vol. 28, no. 4, pp. 57–65, Aug. 2021.

 ISBN: 978-1-61208-940-9