A Cooperative and Coded Communication Scheme using Network Coding and Constructive Interference for Information-Centric Wireless Sensor Networks

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Abstract—**This paper presents 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 to enhance data distribution and reduce radio interference between relay nodes. The results of computer simulations demonstrate the recoverability of forwarding data under the cross-interference environment and improvement in caching-data spread.**

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

I. INTRODUCTION

Internet-of-things applications have become widespread across various domains, such as smart cities, industrial automation, healthcare, and "smart everything." This has been introduced to leverage Internet connectivity to turn objects into smart objects and enables devices to exchange information with each other and make decisions. For instance, smart-city applications can provide a solution for the issues resulting from urbanization, including social needs, and governmental structures [2]. These applications have led to an explosive increase in the number of edge-node devices. In other words, success in this context depends on the effective deployment of advanced wireless network technologies. In this occasion, machine-type communications, which are quite different from traditional human-type communications, must be investigated extensively. The features of these systems include low power, broad coverage, ultra-density, and mobile edge computing [3]. In addition, 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 areas where a natural disaster has occurred [4]. Disaster-resilient smart cities require secure and reliable wireless communication because it is of extreme importance when dealing with users' health records and other sensitive information [5].

Various wireless communications and network protocols have been investigated to meet different requirements regarding the collection, distribution, security, and privacy of sensing data. Towards this end, wireless sensor networks (WSNs) have become an integral part of the future Internet framework to take advantage of various technologies across horizontal and vertical domains. One promising element of the solution for the above technique is the use of an information-centric network (ICN), (e.g., a content-centric network or named-data network). This next-generation network architecture is poised to replace the current IP-based networks [6]. It natively supports features, such as abstraction, naming, and in-network caching, which enables decoupling the data from its original location and adopting individual data-based security at the network-layer level. Therefore, the idea of ICN with WSNs is a suitable combination for the aforementioned background, which yields information-centric wireless sensor networks (ICWSNs).

ICWSNs implement a packet flooding (broadcasting) strategy, which generates numerous requesting packets, resulting in high traffic and network congestion. Although this paper does not focus on congestion control, it is essential to consider congestion when aiming to enhance ICWSNs. Therefore, it is imperative to develop a new ICN-based network protocol and friendly wireless communications technologies. However, to the best of our knowledge, suitable wireless systems have not yet been sufficiently investigated with respect to integrating communication, caching, computing, control, sensing, and localization technologies [7]. Such systems present several technical concerns, including limited battery power, range between devices, bandwidth, disconnectivity, network overload, data redundancy, communication overhead, network lifetime, lack of information, and data integration difficulties. As a medium access control (MAC) and physical layer (PHY) protocol underpinning ICWSNs, the ad-hoc wireless networking, and multi-hop relay networking techniques can be used as clues for practical usage. These technologies enhance the domain of autonomous-distributed services at the cost of efficient utilization of system resources [8].

We propose a cooperative communication scheme for underpinning effective ICWSN frameworks. The concept of cooperative communications 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. The proposed scheme uses a network coding (NC) [9] technique to minimize network traffic on relay nodes. However, NC-encoded packets generate an area of epidemic-packet collisions and congestion because the neighbor relay nodes forward the packets at the same time. Furthermore, in some cases, WSN devices simplify the protocol stacks, and omit synchronization and

collision avoidance mechanisms. The proposed scheme can reduce the radio interference among multiple relay nodes during the data flooding process by using constructive interference—if receiver-side nodes can detect a superposition of baseband signals from multiple transmitter-side nodes, the interference can be ignored [10].

The previous work [1] illustrated a blueprint of this study. On the other hand, the contributions of this paper are as follows: we propose a MAC/PHY protocol and evaluate the advantage of combining NC and constructive interference for the proposed scheme through fundamental PHY characteristics. We also evaluate the improvement to caching data deployment as a result of the proposed scheme.

The remainder of this paper is organized as follows. Section II presents an overview of the basic principle of cooperative communications. Section III introduces the proposed scheme, and Section IV presents the numerical results. Section V provides related work. Section VI concludes the paper with a brief summary and mention of future work.

II. COOPERATIVE COMMUNICATION TECHNOLOGIES

In this section, we introduce the key technologies, the NC technique and constructive interference that we use in the proposed scheme.

A. Network coding for cooperative communications

Communication between the 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, 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 A and $\mathbb{B}$'s data of B, and $\mathbb{C}$ exchanges them as relay nodes. In this case, the data transmission is completed in four steps: sending A from $\mathbb{A}$ to $\mathbb{C}$, sending B from $\mathbb{B}$ to $\mathbb{C}$, forwarding A from $\mathbb{C}$ to $\mathbb{B}$, and forwarding 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 A and B by utilizing an exclusive OR (XOR) operation, the data transmission procedure can be reduced to three steps: sending A from $\mathbb{A}$ to $\mathbb{C}$, sending B from $\mathbb{B}$ to $\mathbb{C}$, and forwarding $A \oplus B$ from $\mathbb{C}$ to $\mathbb{A}$ and $\mathbb{B}$ during broadcasting. After receiving $A \oplus B$, $\mathbb{A}$ can restore B by $(A \oplus B) \oplus A$, and $\mathbb{B}$ can restore A in the same manner. Note that $\oplus$ denotes the XOR operator.

We note that if it is unnecessary for the relay node to know the exact source data, in other words, if the relay node does not need to cache the data, a physical-layer NC (PHY-NC) method can be adopted. In the PHY-NC method, the NC data is not decoded the individual data separately, and the combined signals are received simultaneously from two nodes into NC data. Therefore, general NC is introduced to decrease the number of required time slots to three, whereas PHY-NC can further reduce until two slots [11][12].
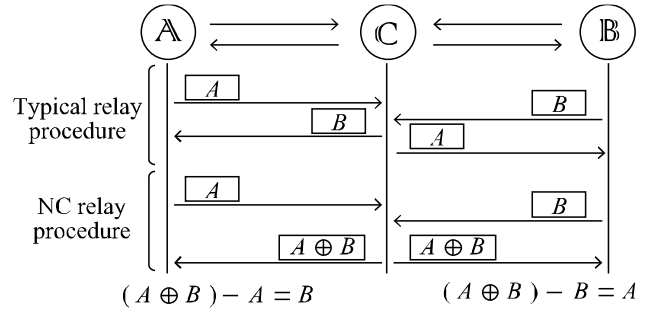

Figure 1. Network model of example node deployment for network coding technqiue in the proposed scheme

B. Constructive interference

Wireless communications cause interference whenever spatially close nodes transmit concurrently, namely, when they generate signals that overlap in time and space, and share the same radio frequency. Interference is generally disruptive and lowers the probability of successful packet reception. In contrast, when interference is constructive, if receiver-side nodes can detect a superposition of baseband signals from multiple transmitter-side nodes, the interference can be ignored. Namely, the superposition of several tolerable out-of-phase carrier signals enables correct detection with high probability. Constructive interference is especially useful when more than two nodes transmit concurrently. For instance, a flooding-based communication, such as in WSNs, is suitable and can propagate a packet for several (multi-hop) transmissions through the entire network without serious collisions.

III. PROPOSED SCHEME

ICN decouples the data from its original location using a name-based data-centric network scheme, which enables to cache and delivering the 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, MAC protocol, and PHY protocol.

A. Proposed cooperative communications scheme

In-network caching—where each node duplicates the frequently used data by leveraging their embedded local (cache) storage—helps to decrease the end-to-end delay and reduce the network traffic. To accelerate the effect of in-network caching in ICWSNs, the nodes should actively accumulate the data as cached data. One of the key features of a wireless communication system is an overhearing phenomenon in which neighbor nodes can receive data whether or not it is desired. For example, in Figure 2(a), when $\mathbb{A}$ sends A to $\mathbb{C}$, $\mathbb{F}$, and $\mathbb{D}$ can also receive A; likewise, when $\mathbb{B}$ sends B to $\mathbb{C}$, $\mathbb{G}$ can also receive B. Therefore, the scheme achieves in-network caching for the nodes located along the

routing path (on-path caching) as well as those around the routing path (off-path caching).

For two-way network traffic, in other words, when the routing paths overlap in opposite directions, the NC technique can reduce the number of forwarded packets. In the relay phase, as shown in Figure 2(b), $\mathbb{C}$ transmits $A \oplus B$ instead of A or B. Here, due to the overhearing phenomena, $A \oplus B$ from $\mathbb{C}$ can be received from $\mathbb{A}$ and $\mathbb{B}$ as well as from $\mathbb{D}$ and $\mathbb{E}$. Therefore, as the assist phase in the proposed scheme, as shown in Figure 2(b), $\mathbb{D}$ and $\mathbb{E}$ also send $A \oplus B$ as a helper with $\mathbb{C}$ by performing multiplexing. As a result, if $\mathbb{A}$ fails to receive $A \oplus B$ from $\mathbb{C}$, it can be recovered by utilizing $A \oplus B$ from $\mathbb{D}$ due 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.

To support the cooperative mechanism, each node has three phases: transmit, relay, and assist. Every node regularly maintains standby (e.g., $\mathbb{F}$ and $\mathbb{G}$), and the status is changed to the transmit phase when the node makes a data transmission request (e.g., $\mathbb{A}$ and $\mathbb{B}$). While receiving surrounding (overheard) data, if the node receives two different data which should be forwarded, the status moves to the relay phase (e.g., $\mathbb{C}$). However, if the received data is NC-encoded data, the status switches to the assist phase (e.g., $\mathbb{D}$ and $\mathbb{E}$). The details of the proposed scheme's signal processing will be described in Section III.D.

B. Proposed MAC protocol

We assume the pure (unslotted) Aloha method is used as a channel access protocol in the MAC layer, which has been widely adopted as a channel access protocol in commercial low-power wide-area networks. An uncomplicated protocol is assumed to simplify the device implementation (including low-energy consumption), and because the synchronization among nodes is not practically available in ICWSNs. 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 3, in the proposed scheme, the relay nodes and assist nodes forward the NC-encoded data immediately (in the relay and assist phases), so collision and interference in a regional area are inevitable.

The proposed scheme utilizes constructive interference to tackle the issues regarding collision and interference caused by forwarding multiple NC-encoded packets. Namely, as shown in Figure 3, if the received NC-encoded packets (e.g., $A \oplus B$) are immediately forwarded in the assist phase, the interference of these packets (that are transmitted by $\mathbb{D}$ and $\mathbb{E}$) can be reduced. The primary reason that we assume an unsophisticated MAC protocol is to integrate the constructive interference effectively in the assist phase. In WSNs, constructive interference has not been extensively exploited because it is difficult to attain sufficiently accurate synchronization and highly predictable software delays are required. However, this approach is suitable for the scenarios in which the proposed scheme is applicable (i.e., in the relay
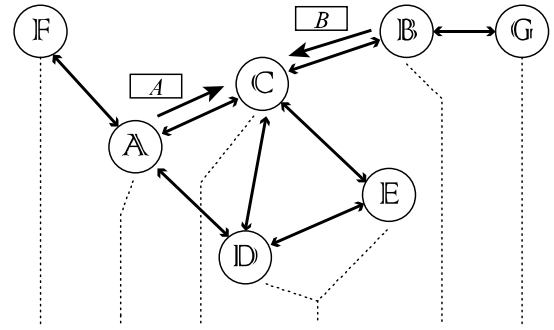
(a) Network model of example node deployment
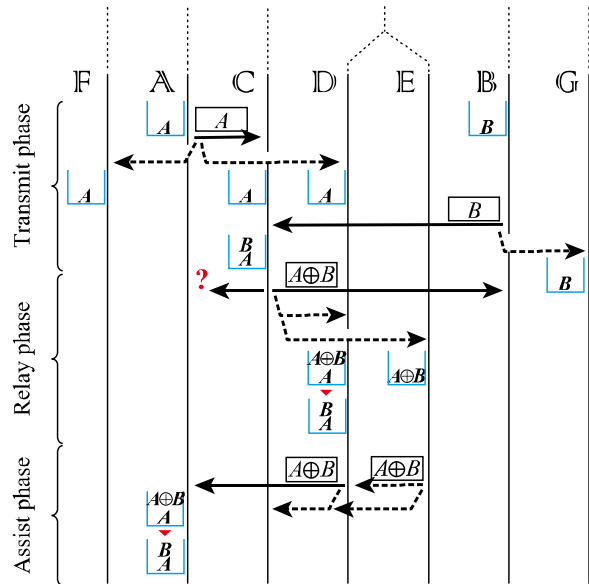
(b) Message and data flow of proposed data-forwarding processing

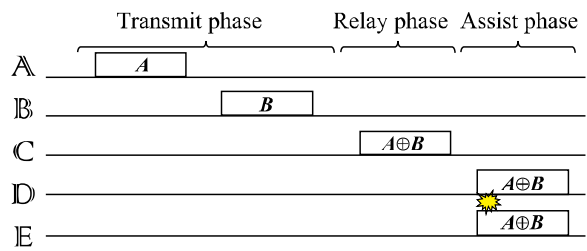Figure 2.   Proposed cooperative communication scheme

Figure 3.   Baseline scenario of proposed scheme in MAC layer

and assist phases). Note that in cases where different data are in conflict with each other (destructive), the proposed scheme cannot be applied, which is beyond the scope of our present study.

C. Proposed PHY protocol

In the modulation scheme of digital wireless communication systems, $K (= \log_2 M)$ bits data are placed on the phase and/or amplitude of the transmitted waveform. Let T denote the time period required to transmit one symbol of the M-ary modulation method. In the baseband representation of the modulated waveform, a symbol $(s_I, s_Q) \in \mathbb{R}^2$ is defined as

$$(s_I, s_Q) \triangleq (s_{i_1}, s_{i_2}), (i = 1, 2, \cdots, M) \qquad (1)$$

where $\mathbb{R}$ denotes the set of real numbers. A transmitted signal waveform, $s(t)(0 < t < T)$ is then represented by

$$s(t) = \Re(x(t) \, e^{j2\pi f_c t}) \qquad (2)$$

where the operator $\Re(\cdot)$ denotes real part, f_c denotes a radio-frequency (RF) carrier waveform, and $x(t) \triangleq s_I + js_Q$.

On the receiver side, if we ignore the effects of multipath fading and shadowing for simplicity, the wireless link is characterized as an additive Gaussian noise (AWGN) channel. Then, the received signal waveform $y_\ell(t)$ is expressed as

$$y_\ell(t) = s(t) + n_\ell(t) \qquad (3)$$

where $n_\ell(t)$ is the AWGN, i.e., its (stochastic) random variable is depended on a normal distribution. During the relay and assist phases, the total signals received from the L nodes with a minute offset τ is given by

$$y(t) = \sum_{\ell=1}^{L} s(t) \, \delta(t - \tau_\ell) + n_\ell(t) \qquad (4)$$

where the operator $\delta(\cdot)$ means time shift by τ.

D. Signal processing of MAC and PHY protocols

The signal processing procedure of the proposed scheme is shown in Figure 4(a). The data frame corresponding to the sensing data is temporarily stored in the buffer memories and is pending until allowed to transmit from the transmission controller, along with the cooperative communications' data for the relay and assist phases. Figure 4(b) shows the states of the transmission controller: receive, transmit, relay, and assist. The transmit, relay, and assist states correspond to the three phases and append the receive state for standby. These states are switched depending on the state sequences (arrows between states) that are triggered by the radio events. When the node device needs to transmit the data, i.e., the data frame has arrived at the data buffer, the state is switched from receive to transmit, and then the data are sent. Similarly, while the node device is overhearing incoming data from the neighbors, when the NC-encoded data arrives, the state is switched from receive to assist. After data transmission is complete, it is switched back from the transmit or assist states to receive.

Meanwhile, the transmission controller periodically checks the status of neighbor nodes and has the database regarding the combination of relayed nodes, e.g., $\mathbb{C}$ should
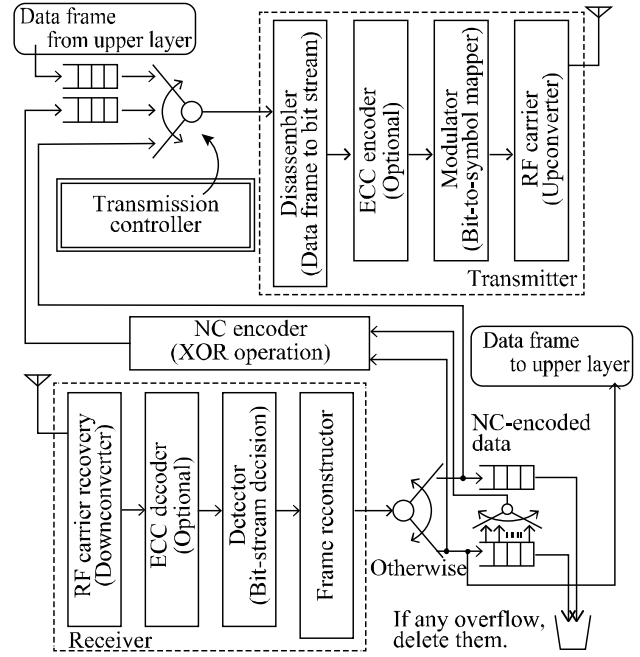
(a) Signal processing of the proposed scheme
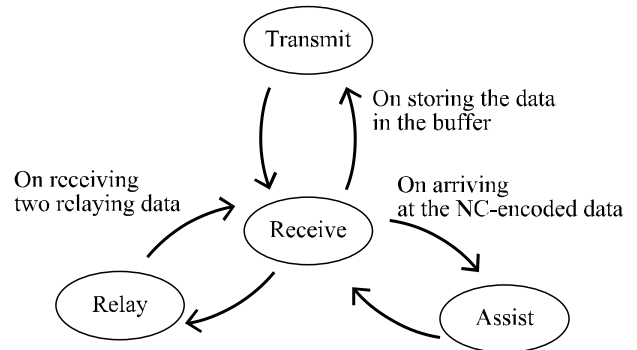
(b) State of the transmission-data controller

Figure 4. Signal processing of the proposed scheme

know $\mathbb{A}$ and $\mathbb{B}$ are the combinations of relayed nodes. Therefore, when the node device contains two data from the relayed nodes, it switches from receive to relay, and then it fulfills the relayed procedures. In this paper, 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. Note that, if the node device is not in the receive state, it cannot switch between the transmit, assist, and relay states.

In the transmitter, as shown in Figure 4(a), the data frame is disassembled to the bit stream. Then the bit-based data are mapped into bit-to-symbols at the modulator (mapper) and superimposed on the RF carrier waveform to the antenna. In the receiver, the received signal is down-converted to the

baseband, demodulated, and detected, and then the recovered data are reconstructed to the data frame. The received data are classified as NC-encoded data or otherwise and respectively stored to data buffers. In addition, the error control coding (ECC) encoder and decoder are inserted between the frame (de)structure and (de)modulator if necessary. Unlike ordinal flooding mechanisms, the proposed scheme does not add any backoff, and the nodes transmit the same packet simultaneously immediately after the packet reception in the assist phase. By exploiting constructive interference phenomena, the proposed scheme can maintain a high packet reception rate despite allowing concurrent transmission. Therefore, if the received NC-encoded packets are forwarded immediately in the assist phase, the interference of packets transmitted will be reduced.

IV. COMPUTER SIMULATION

To evaluate the proposed scheme, we investigated the restorability of the baseband signal by using constructive interference and improvement in data caching among nodes.

A. Simulation environment for PHY performance

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 when $\mathbb{C}$ sends the NC-encoded data in the relay phase, $\mathbb{D}$ and $\mathbb{E}$ forward the data in the assist phase, and then $\mathbb{A}$ receives them (Figure 2). The computer simulation is conducted using the Matlab simulator. The waveforms of the radio signal arriving from the assist nodes are generated using the same data and system but with a time gap of τ.

The frame length was set as $1,000 \times \log_2 M$ bits, and the information bits were assigned by random values on the basis of the Bernoulli distribution with equal probability. Considering the wireless module to be installed in the WSN node device, the modulation scheme uses phase shift keying (PSK), in which the bits are superimposed on the phase of the carrier waveform. In particular, in (1), we consider $M = 2, 4$, and 8 for M-ary PSK methods, i.e., BPSK, QPSK, and 8-PSK, respectively. In addition, the bit-to-symbol mapping rule was used based on the optimum mapping pattern (Gray code). To minimize the complexity of the simulation and evaluate the fundamental performance of the proposed scheme, we ignore the fading and shadowing as in (3) due to SN mobility (i.e., assuming SNs are statically deployed and utilized). Namely, the channel is dominated by AWGN, and we assume that the number of assist nodes, $L = 2$ in (4), and their transmission power are the same parameters. We used a normalized signal-to-noise ratio (SNR) (that is, strictly SNR per bit or E_b/N_0) to represent the transmitted power in order to compare the performance of the different modulation schemes as a same condition.

B. Comparison of modulation methods

The simulation parameters are listed in Table I, and the result of bit error ratio (BER) performance of the different modulation methods are illustrated in Figure 5. The parameters are 1) type of modulation: BPSK, QPSK, and 8-

TABLE I.   SIMULATION PARAMETERS

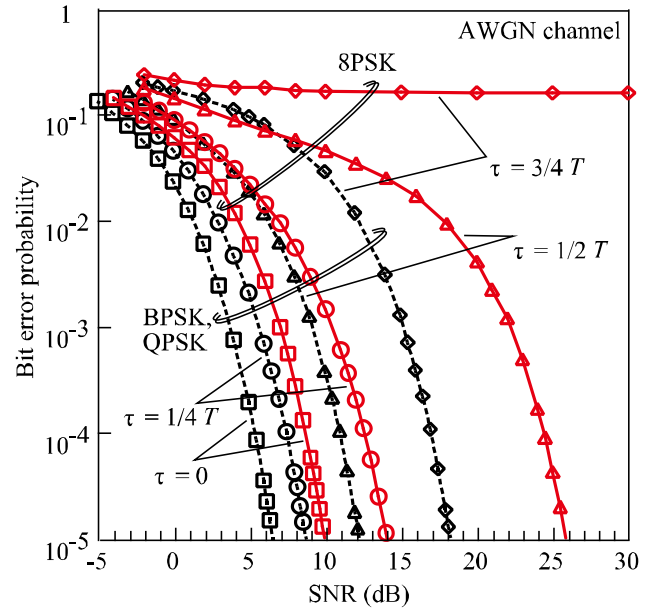| Terms	Values
Modulation method	BPSK, QPSK, 8PSK with Gray mapping rule
Frame length	1,000 bit (BPSK), 2,000 bit (QPSK), 3,000 bit (8PSK)
Error-control coding	N/A
Detector's decision type	Hard-decision
Sampling rate of waveform	16 samples/symbol
Channel model	AWGN channel

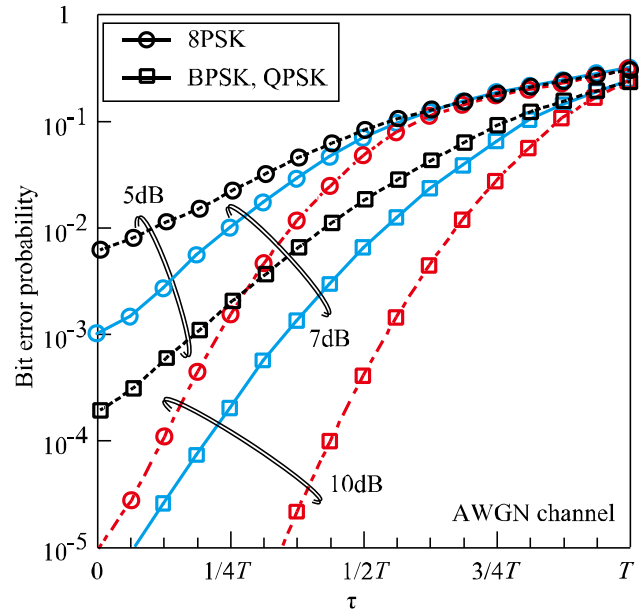Figure 5.   Bit error probability vs. SNR for BPSK, QPSK, and 8-PSK methods

Figure 6.   Bit error probability vs. time gap τ for BPSK, QPSK, and 8-PSK methods when SNRs were 5, 7, and 10 dB
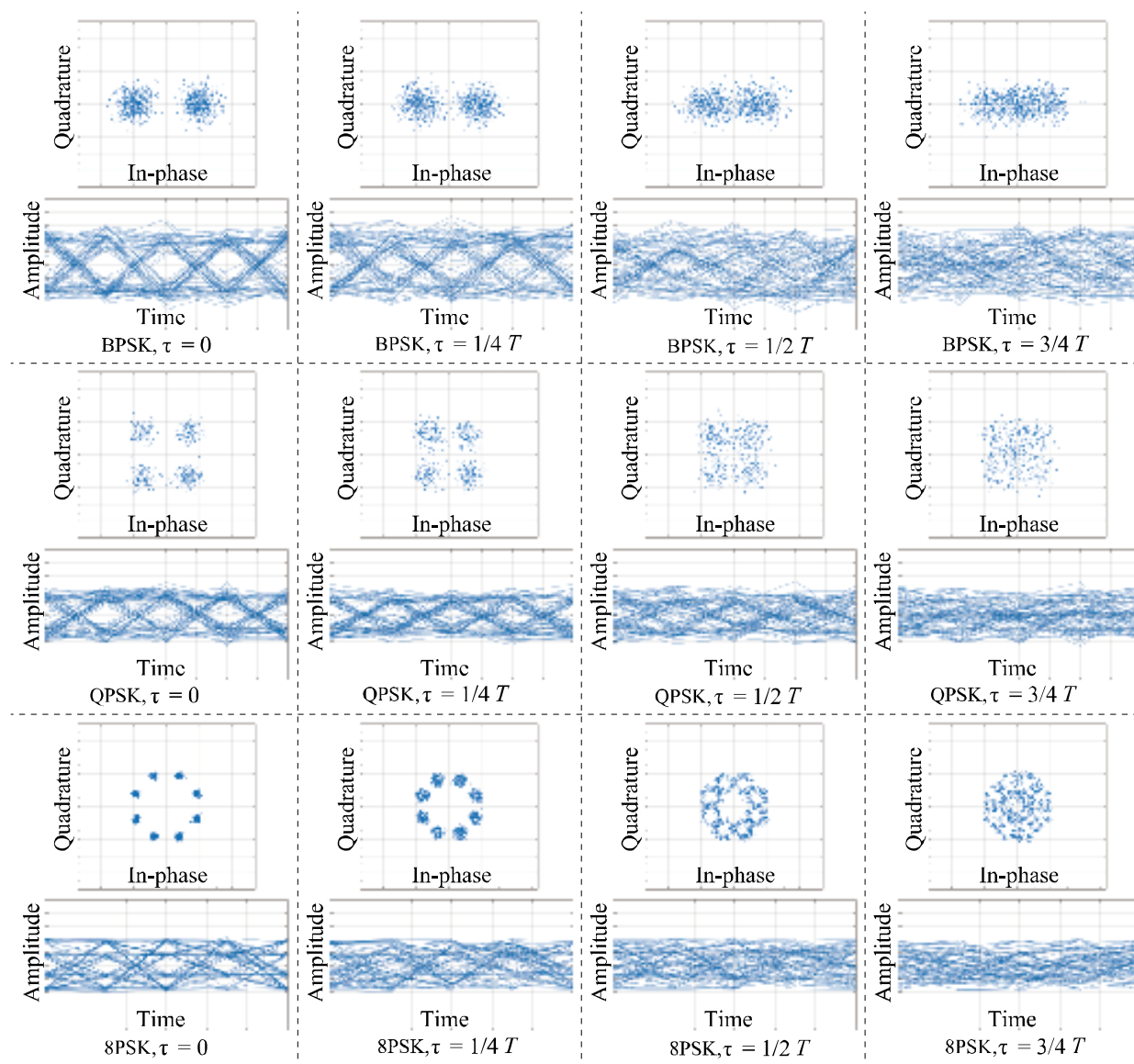
Figure 7.   Perforamnce of teceiver-side detector, including constellation diagram and eye diagram, for received signals with a time lag.

PSK, 2) time gap: $\tau = 0$, $(1/4)$ T, $(1/2)$ T, and $(3/4)$ T, and 3) SNR. The curves of BPSK and QPSK were overlapped (i.e., the result of BPSK and QPSK were the same) because their signal constellations (i.e., bit-to-symbol mapping pattern in (1)) are orthogonal. This indicates that the BPSK/QPSK methods are more effective than the 8-PSK method, and the major error mechanism is the time gap.

In the BPSK and QPSK methods, the SNR for 10^{-3} BER are 3.8 dB, 5.7 dB, 9.2 dB, 15.2 dB, and the SNR for 10^{-5} BER are 6.6 dB, 8.8 dB, 12.3 dB, and 18.3 dB for $\tau = 0$, $(1/4)$ T, $(1/2)$ T, and $(3/4)$ T, respectively. In contrast, in the 8-PSK method, the SNR for 10^{-3} BER are 7.0 dB, 10.5 dB, and 22.2 dB, and the SNR for 10^{-5} BER are 10 dB, 14.1 dB, and 25.9 dB, respectively. In particular, the bit errors cannot be reducible (BER floor) in the case of 8-PSK with $\tau = (3/4)$ T,

even if the SNR is set as very large. Therefore, when the transmission data rate is higher (i.e., M is set as a large value), it is difficult to gain the effect of constructive interference. However, this is not a serious concern because the application service in which the proposed scheme will be deployed does not require high-speed and high-capacity wireless communications.

To investigate the effect of τ on the proposed scheme, in Figure 6, the results of the BER performance when τ is varied. The major parameters are considered as follows: 1) type of modulation: BPSK, QPSK, and 8-PSK, 2) SNR: 5 dB, 7 dB, and 10 dB, and τ. Increasing τ leads to a BER degradation, and the BER curve is not linear, i.e., the gradient of the BER curve becomes gradually relaxed, this means the effect on the

TABLE II.   SIMULATION PARAMETERS

Terms	Values
Modulation method	BPSK with Gray mapping rule
Frame length	1,000 bit (BPSK)
Error-control coding	Uncoded, Convolutional coding with Viterbi decoding
Detector's decision type	Hard-decision
Sampling rate of waveform	16 samples/symbol
Channel model	Additive white Gaussian noise

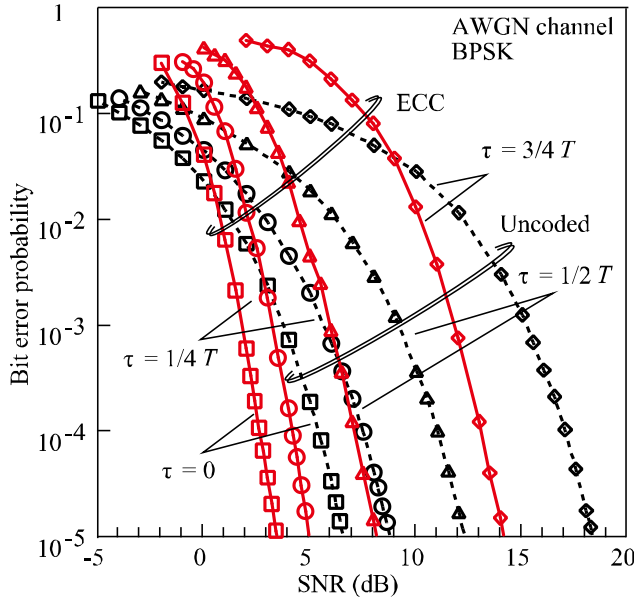Figure 9.   Number of successfully received nodes and cached data

Figure 8.   Bit error probability vs. SNR with and without ECC technique for BPSK method

BER should be significantly considered in the region where τ is as small as possible.

C. Received signal for detection

In the receiver, Figure 7 shows a received signal to be handled, i.e., the signal to be demodulated and detected. The parameters are 1) type of modulation: BPSK, QPSK, and 8-PSK, 2) time gap: $\tau = 0$, $(1/4)\,T$, $(1/2)\,T$, and $(3/4)\,T$, 3) SNR set as 10 dB, and 4) the constellation and eye pattern (diagram) of the received signal. The results of the detector's performance indicate that the cases of $\tau = 0$, $(1/2)\,T$, and $(1/2)\,T$ had a clearly separated constellation of received signals and a clear eye pattern, while $\tau = (3/4)\,T$ had the opposite result and thus the detector could not decide (estimate) the transmitted data. This result is also well linked to the effects of τ on bit error probability, as shown in Figures 5 and 6.

D. Effect of error control coding scheme

In general, wireless communication systems mitigate packet errors using automatic repeat request and forward error correction. The former is out of scope in this paper because
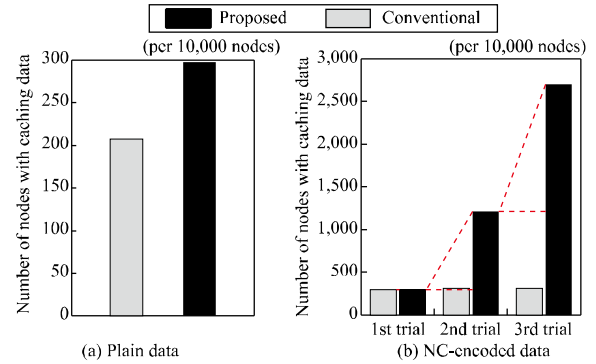
we particularly focus on the relay and assist phases, while the latter is considered in this section. If a powerful ECC scheme is adopted, the processing delay will increase significantly. This leads to an increasing τ, which is detrimental to the proposed scheme. In addition, as the aforementioned results show, the BPSK method performs more noise resistance (in terms of bit error probability) than other methods, and it is commonly used in the node devices (i.e., that is supported as a basic modulation method) that consist of the application services in which the proposed scheme is deployed. Therefore, the simulation parameters are listed in Table II, and the results of bit error probability with and without the ECC method in the BPSK method are shown in Figure 8. The parameters are 1) type of modulation: BPSK, 2) type of ECC scheme: uncoded and convolutional code with Viterbi decoding scheme, 3) time gap: $\tau = 0$, $(1/4)\,T$, $(1/2)\,T$, and $(3/4)\,T$, and 4) SNR.

The results illustrate that for $\tau = 0$, $(1/4)\,T$, $(1/2)\,T$, and $(3/4)\,T$, thanks to introducing the ECC scheme, the SNR for 10^{-3} BER can improve by 2.0 dB, 2.5 dB, 3.2 dB, and 3.4 dB, and the SNR for 10^{-5} BER can improve by 3.2 dB, 3.8 dB, 4.1 dB, and 4.1 dB, respectively. Meanwhile, in the regions with small SNR (less than 0.5 dB, 1.7 dB, 3.8 dB, and 9.0 dB for $\tau = 0$, $(1/4)\,T$, $(1/2)\,T$, and $(3/4)\,T$), BER performance with ECC cannot be improved; thus, there is no advantage to using the ECC scheme in these SNR regions.

E. Effectiveness of proposed scheme

To illustrate the benefit of the proposed scheme, we performed another evaluation using computer simulation implemented in C++ language. This simulation aims to illustrate that the proposed scheme can assist in maximizing the number of nodes with caching data. In the simulation, 10,000 nodes were deployed in a 1-km² 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. Because the assist nodes that receive the first-forwarded data from the relay station will transmit the data twice, and the nodes that receive the second-forwarded data will transmit them once. The end of the assist phase can align with the end

of the relay phase, and the proposed scheme can prevent infinite data flooding.

As seen in Figure 9(a), the number of successfully cached nodes per 10,000 was improved by 43.5% as a result of the assist nodes. For spreading the NC-encoded data, as shown in Figure 9(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 to decode the NC-encoded data, plain data is required, e.g., either A or B for $A \oplus B$.

V. RELATED WORK

The combination of NC and ICN has become a growing research interest. Montpetit et al. [13] utilized this combination in the internetworking layer by applying the NC technique to enhance the performance of data forwarding in ICNs. Mekbungwan et al. [14] 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. Their system design was based on the store-carry-and-forward method in delay-torrent networking store-carry-and-forward method in order to reduce the amount of network traffic on relay nodes. For 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, the concept of which is the same as the path-diversity technique [15]. 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. [16] proposed a task-oriented communication method 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.

VI. CONCLUSION

We proposed a cooperative communication scheme using the NC technique with constructive interference for ICWSNs. The numerical results of our initial evaluation of the scheme indicated that a small gap of signals could be tolerated, and the proposed scheme could contribute to the distribution of cached data. In future work, because the recoverability of the received data depends on the signal gaps of the forwarded data, we should further investigate a technique that separates them. Moreover, we will expand the practical scenarios in which our scheme can be implemented to enhance the quality of service, lifetime, and robustness of the real smart-city site.

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