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

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Biography

Shintaro Mori received his B.S., M.S., and Ph.D. degrees from Kagawa University in 2007, 2009, and 2014, respectively. Since April 2014, he has been with the Department of Electronics Engineering and Computer Science, Faculty of Engineering, Fukuoka University, Japan, where he is currently an assistant professor. His research interests include cross-layer design and wireless sensor networks. He is a member of IEEE, IEICE, ISSJ, and RISP.

For more information, please see my website:

https://cross-layer.com/

Topics of Research Interest

- Smart-city applications
- Blockchain for wireless networks
- Low-power wide area networks
- Information-centric wireless networks
- Unmanned aerial vehicle-assisted wireless networks
- Wireless sensor networks
- Cross-layer design
- Wireless communications

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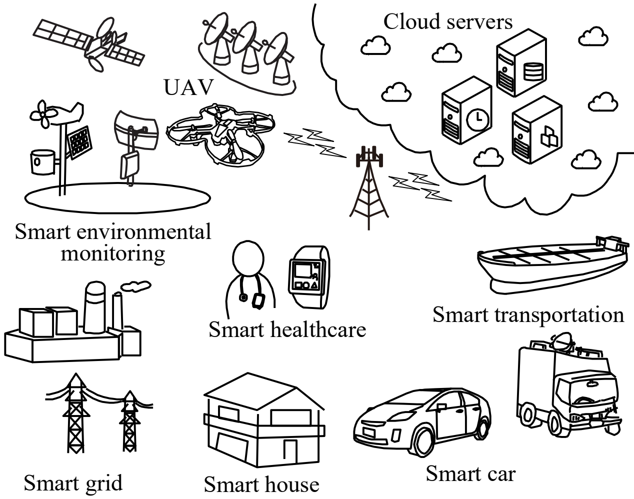
Agenda

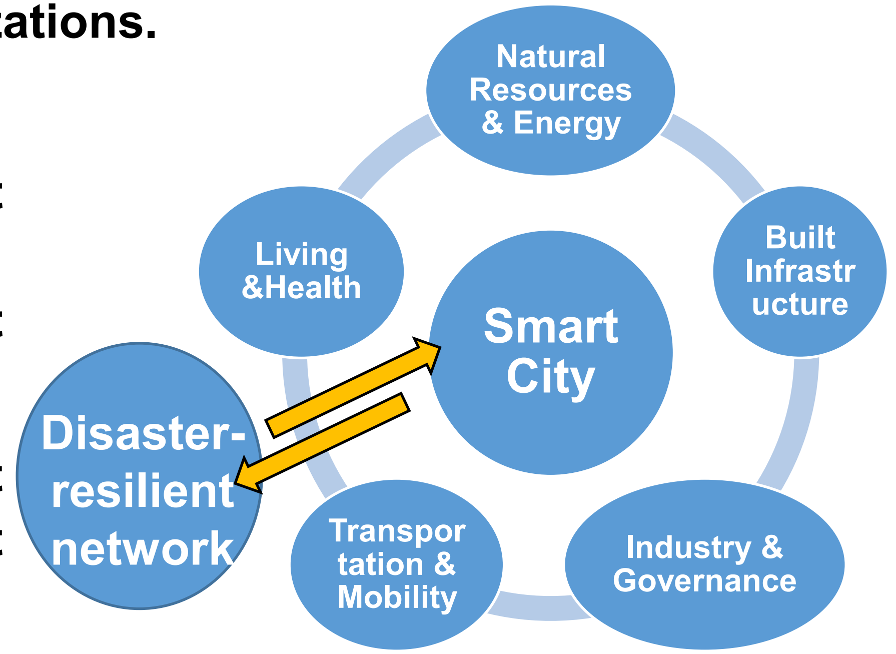
- Introduction
  - Background
  - Contribution
  - Related works
- Cooperative communications
- Proposed Scheme
  - Proposed cooperative scheme
  - Proposed MAC protocol
  - Constructive-interference phenomena
  - Proposed physical protocol
- Computer simulations
- Conclusions

Background

- Internet-of-Things (IoT) applications have become widespread across various domains.
  - Smart cities
  - Industrial automation
  - Human healthcare
  - … smart everything



- Central city areas are increasingly using information and IoT technologies to resolve problems related to urbanizations.
- Smart cities are typically considered a panacea for urban problems, but large-scale natural disasters and global pandemics are significant theme to our daily lives.
- Ensuring the bright future of smart cities, i.e., achieving disaster-resilient smart cities, is of greater importance.



Background

- Smart-city applications are characterized by use of a massive connectivity, known as machine-type communications.
  - ⇔ Different from human-type that in terms of efficiency and reliability.

- Features of these systems include
  - low power
  - broad coverage
  - ultra-density
  - mobile edge computing

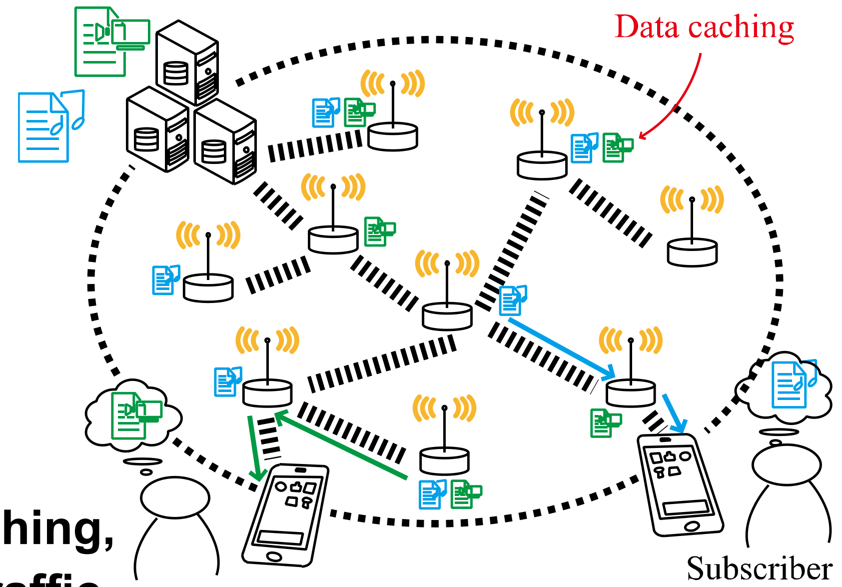
- Today's smart-city solutions face
  - Limitations due to unpredictable and non-uniform traffic
  - Some areas may be outside the wireless network coverage
    - ↳ Rural areas or any area after a disaster has occurred

- 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.
  - ↳ Public-safety broadcasting, mission-critical control, and emergency calls

- Smart-city applications must be resilient and robust, and provide instant communication with various services.

Background

- One promising element of the solution for the above demands is the use of an **Information-Centric Network (ICN)**.
  - Content-centric network
  - Named-data network (NDN)



- ICN natively supports features, such as abstraction, naming, and in-network caching, improves delays and reduces network traffic.

- ICN is a promising architecture that is poised to replace the IP networks.
- 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.

Contribution

- 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.

▽

- However, they come with several technical concerns:
  - Limited battery power, coverage area, bandwidth, dis-connectivity, network overload, data redundancy, communication overhead, network lifetime, lack of information, and data integration difficulties.

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- 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.

Related work

Proposed scheme

- We use a Network Coding (NC) technique to eliminate the amount of network traffic on relay nodes.
- We use a constructive-interference phenomena to reduce the radio interference among multiple relay nodes during data flooding process.

Related work

- For enhancement of forwarding, NC is used in the network layer[11].
- To reduce network traffics, NC-based data dissemination system made up of bulk data was proposed in post-disaster delay-torrent networks[12]
- For the next-generation cellular networks, the packet duplication method is being introduced for high-reliable communications, which is the same concept as the path-diversity technique[13].
- To tackle wireless resource hungry, new task-oriented communication technology in which the waveform superposition property of a wireless channel is exploited to achieve over-the-air aggregation[14].

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[11] M. Montpetit, et al., "Network coding meets information-centric networking: An architectural case for information dispersion through native network coding," *Proc. ACM WS NOM*, pp. 31–36, 2012.
[12] P. Mekbungwan, et al., "An NC-DTN framework for many-to-many bulk data dissemination in OLSR MANET," *Proc. IWCMC*, pp. 964–969, 2015.
[13] S. Baek, et al., "3GPP new radio release 16: Evolution of 5G for industrial Internet of things," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 41–47, 2021.
[14] G. Zhu, et al., "Over-the-air computing for wireless data aggregation in massive IoT," *IEEE Wireless Commun.*, vol. 28, no. 4, pp. 57–65, 2021.

Proposed scheme

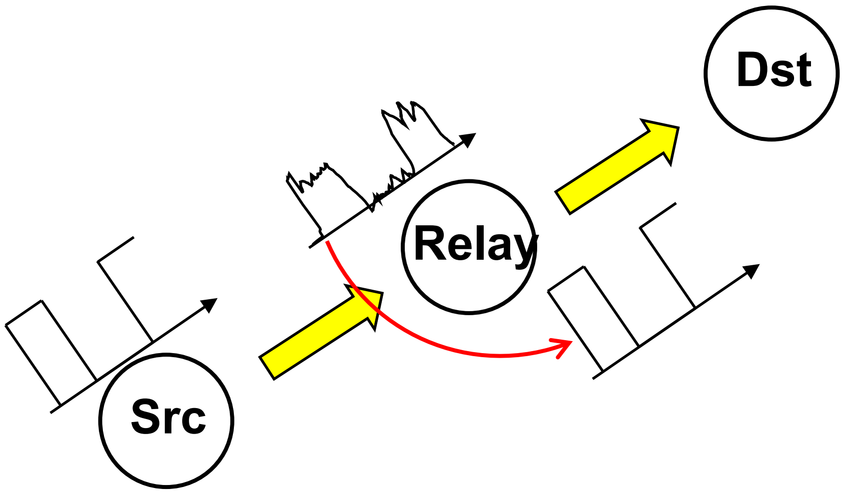
- Proposed scheme
  - We use a Network Coding (NC) technique to eliminate the amount of network traffic on relay nodes.
  - We use a constructive-interference phenomena to reduce the radio interference among multiple relay nodes during data flooding process.
- Summary of ICN scheme
  - ICN decouples the data from its original location using a name-based data-centric network scheme.
    - ↳ It enables the network layer to cache and deliver named data regardless of the availability of the original (source) publisher.
  - ICN can provide content-based security.
    - ↳ All security-sensitive data can be exchanged via wireless channel.

▼

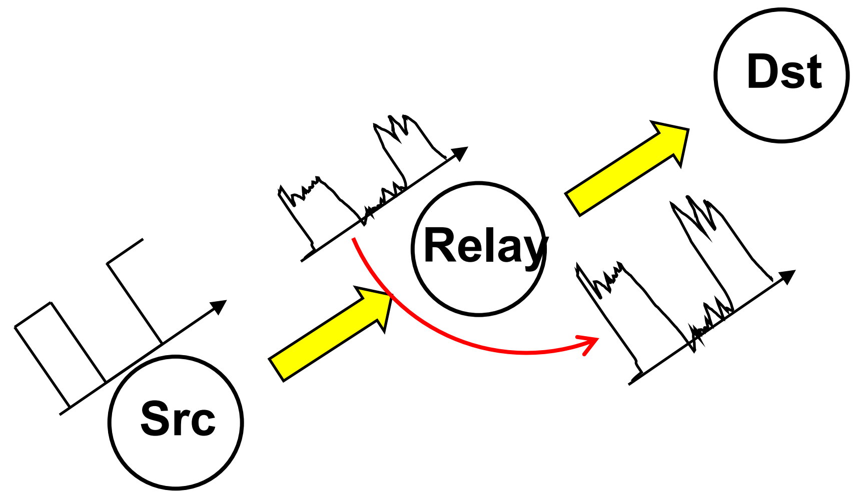
- We provide an overview of the proposed scheme as follows:
  - Proposed cooperative scheme
  - Media Access Control (MAC) protocol
  - Wireless communications protocol

Cooperative communications

- 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:
  - Decode-and-forward relaying method is used to decode the data that reaches the relay node and then re-encode and forward them.
  - Amplify-and-forward relaying method can be selected as a simple forwarding mechanism.



Decode-and-forward relaying method

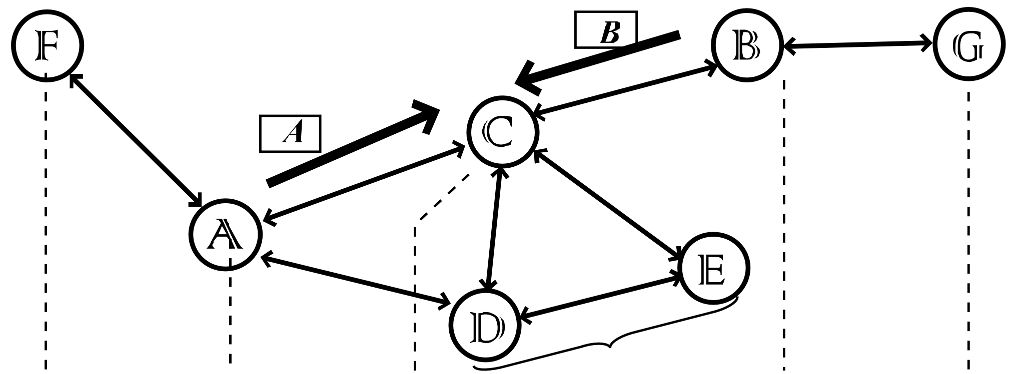


Amplify-and-forward relaying method

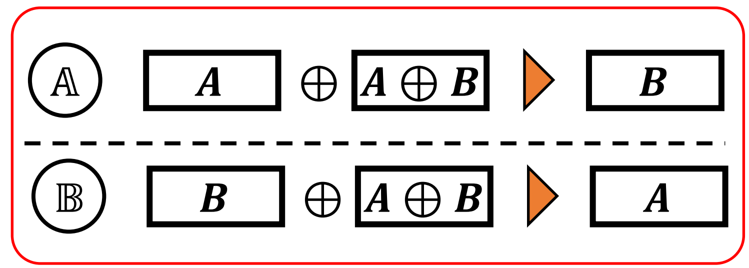
Cooperative communications

- The NC technique is used here with the aim of improving throughput

- General forwarding
  1. Sending A from $\mathbb{A}$ to $\mathbb{C}$
  2. Sending B from $\mathbb{B}$ to $\mathbb{C}$
  3. Forwarding A from $\mathbb{C}$ to $\mathbb{B}$
  4. Forwarding B from $\mathbb{C}$ to $\mathbb{A}$



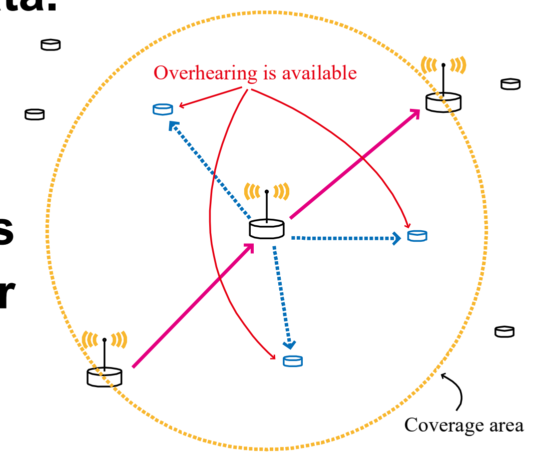
- Cooperative forwarding using NC technique
  1. Sending A from $\mathbb{A}$ to $\mathbb{C}$
  2. Sending B from $\mathbb{B}$ to $\mathbb{C}$
  3. Forwarding $A \oplus B$ from $\mathbb{C}$ to $\mathbb{A}$ and $\mathbb{B}$ during broadcasting
  - Note that $\oplus$ denotes the Exclusive OR (XOR) operator.



- When relay nodes transfer the bit-by-bit mixed data by utilizing an XOR operation, the data transmission procedure can be reduced to three steps.

Proposed cooperative scheme

- To accelerate the effect of the in-network caching scheme, the nodes should actively accumulate the caching data.
  - ↳ It helps to decrease the end-to-end delay and reduce the network traffic.



Overhearing phenomena

- One of the key features of a wireless communications is that it is generally able to overhear what neighbor nodes can receive whether they desire it or not.

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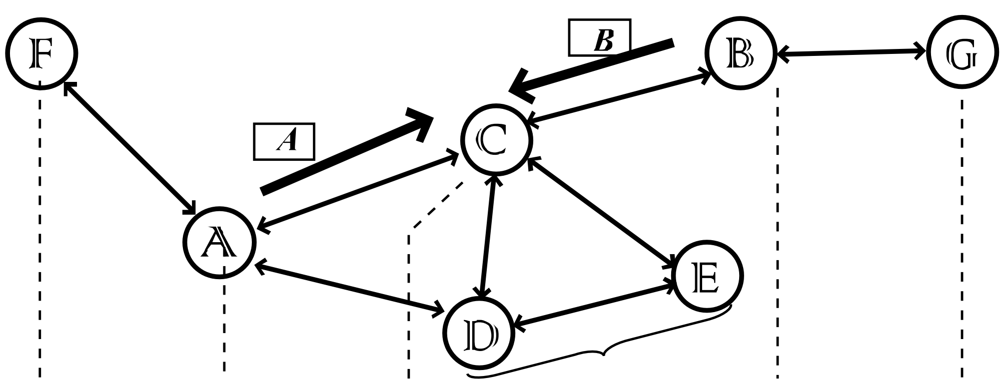
- Off-path caching in the proposed scheme
  - When $\mathbb{A}$ sends A to $\mathbb{C}$, $\mathbb{F}$ and $\mathbb{D}$ can also receive A; similarly, when $\mathbb{B}$ sends B to $\mathbb{C}$, $\mathbb{G}$ can also receive B.
  - Similarly, $A \oplus B$ from $\mathbb{C}$ can be received not only from $\mathbb{A}$ and $\mathbb{B}$ but also from $\mathbb{D}$ and $\mathbb{E}$.

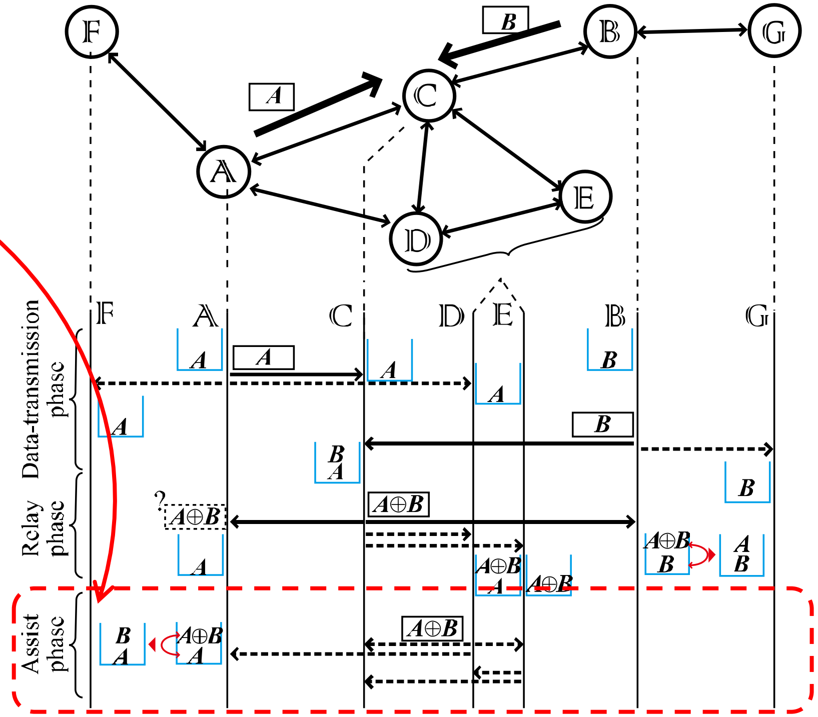


Proposed cooperative scheme

- $\mathbb{D}$ and $\mathbb{E}$ also send $A \oplus B$ as a helper with $\mathbb{C}$ by performing multiplexing in the assist phase

- If $\mathbb{A}$ fails to receive $A \oplus B$ from $\mathbb{C}$, it can recover it by utilizing $A \oplus B$ from $\mathbb{D}$ thanks to the benefit of path diversity afforded through the different links.

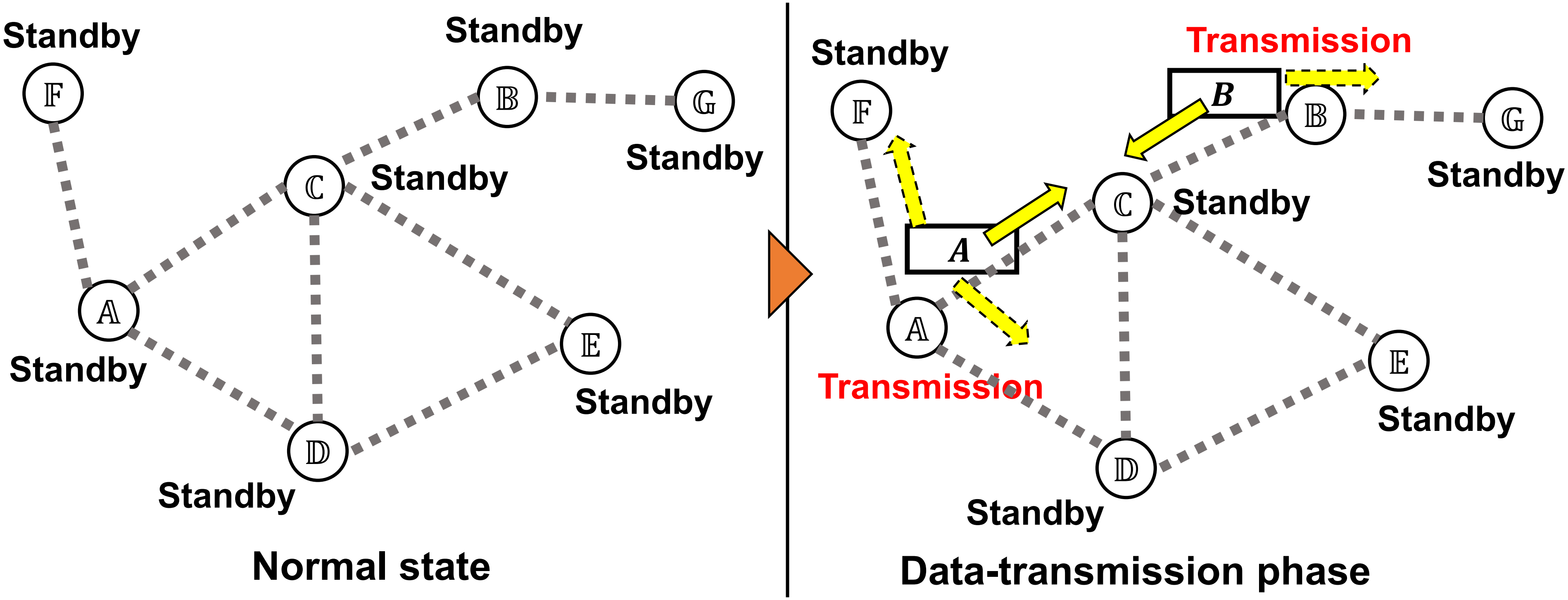
- By using this mechanism, the nodes located around $\mathbb{D}$ and $\mathbb{E}$ but outside the coverage area of $\mathbb{C}$ can be additionally off-path cached, which expands the number of new cashable nodes.



Message and data flow of proposed data-forwarding processing

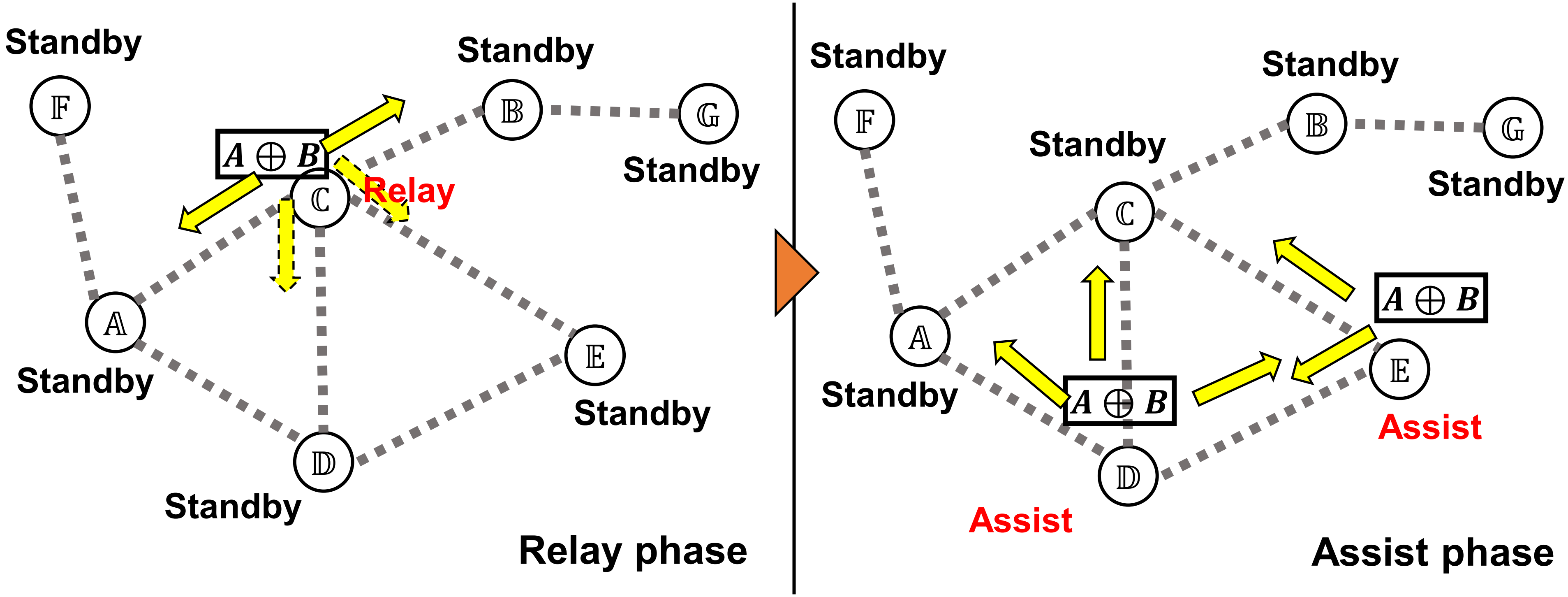
- To achieve this mechanism, we propose a suitable MAC and physical protocols.

Proposed MAC protocol



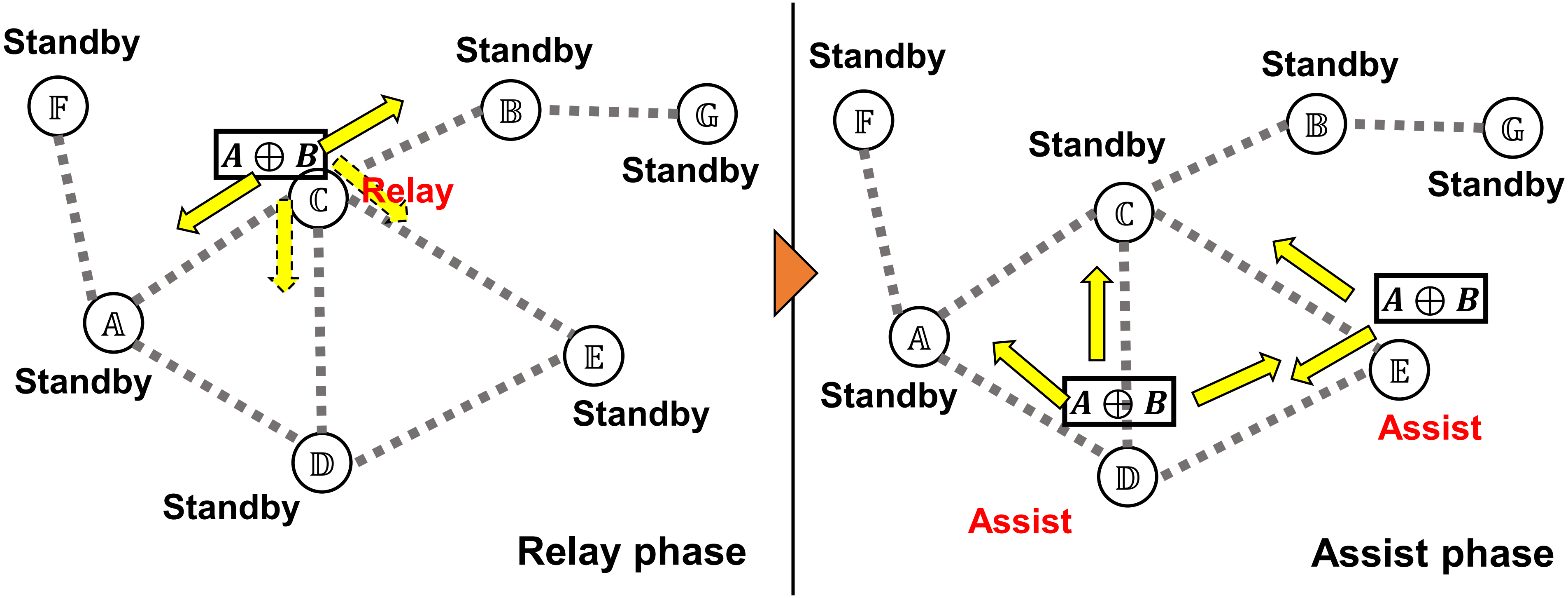
- To support the cooperative mechanism, each node has four states: standby, transmission, relay, and assist.
- Every node regularly maintains the standby state.
- The status is changed to the transmission state when it makes a data transmission request (e.g., 𝔸 and 𝔹).

Proposed MAC protocol



- **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).**
  - **If the received data is NC-encoded data, the status switches to the assist state (e.g., 𝔻 and 𝔼).**

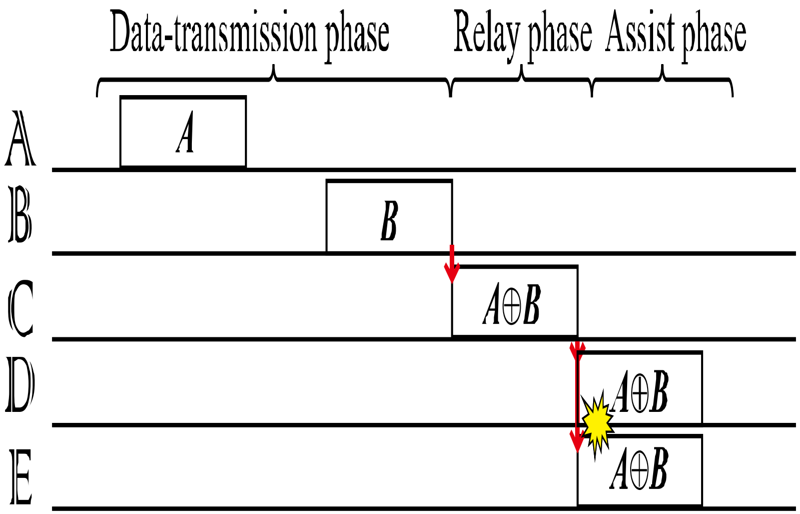
Proposed MAC protocol



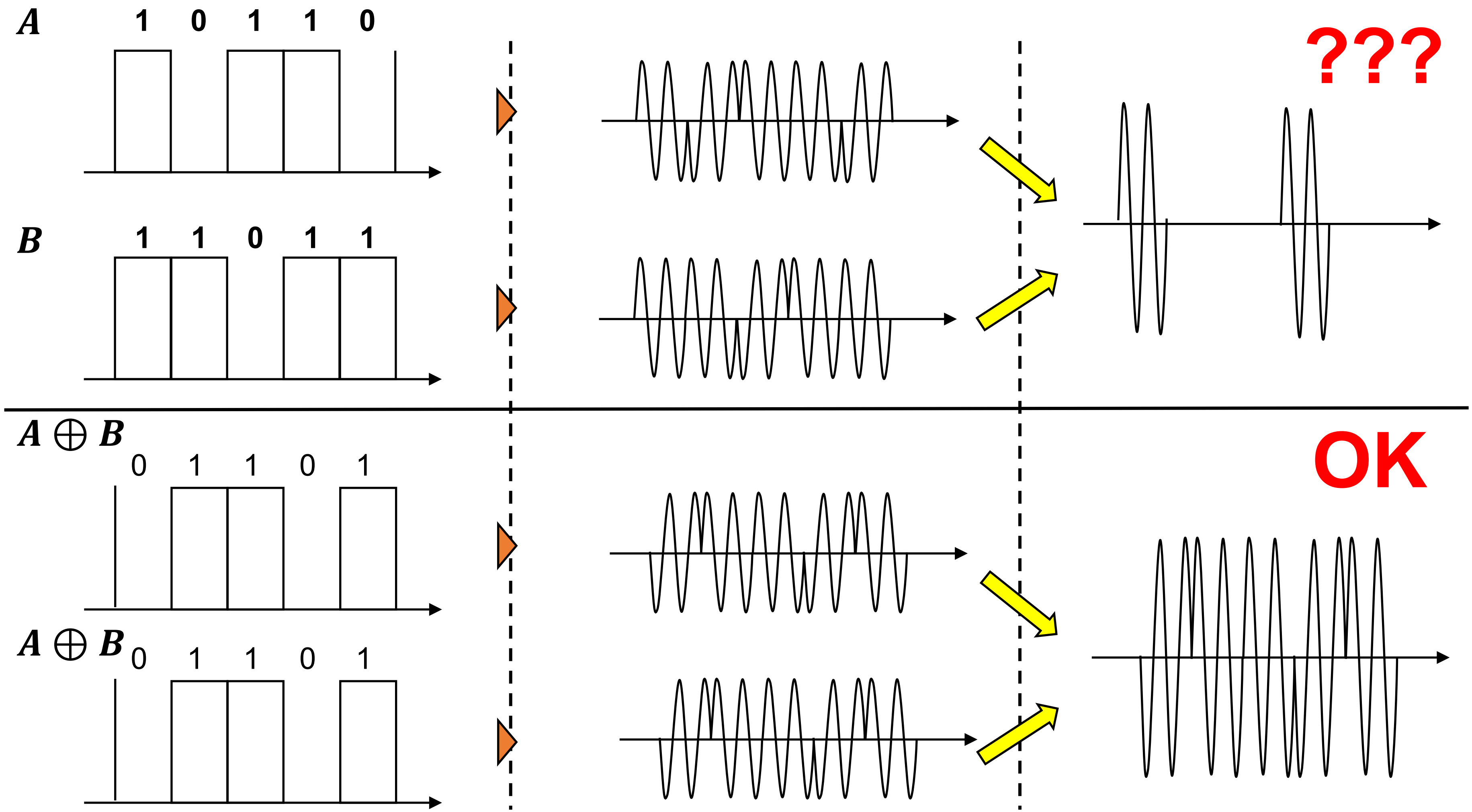
- We assume:
  - Every node knows whether it needs to relay the data.
  - NC-encoded data's number of multi-hops is predefined.
  - Nodes can determine their upper limitation of forwarding in order to avoid unlimited hops.

Proposed MAC protocol

- Proposed scheme is similarly based on current systems.
  - The pure (unslotted) Aloha method has been adopted as a channel access protocol in commercial low-power wide-area networks.
  - The data are iteratively transmitted to eliminate automatic repeat-request messages.
  - ↳ The motivation behind using an uncomplicated protocol is to simplify the device implementation (including low-energy consumption).
- The current wireless communication systems assume that the data transmission has a sufficiently long interval, implying that collision or interference among nodes will not be fatal issues.
- Since the relay nodes and assist nodes forward the NC-encoded data immediately collision and interference in a regional area are inevitable.
- To solve this issue, we use a constructive-interference phenomena in the physical protocol



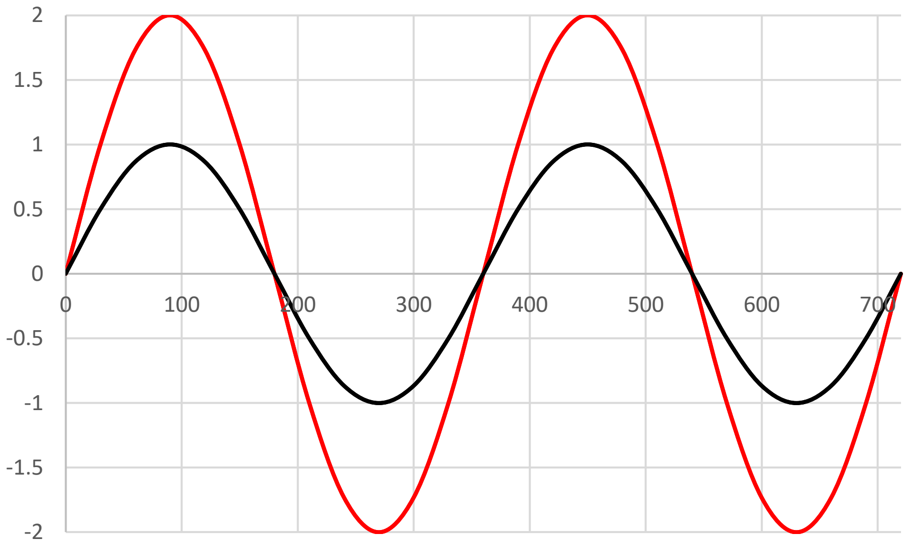
Constructive-interference phenomena



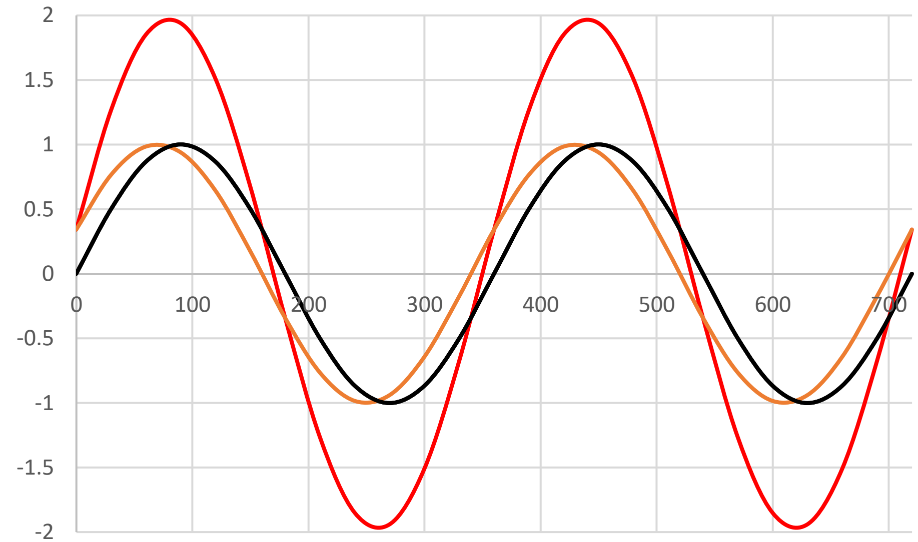
- **Constructive-interference phenomena:**
  - **If receiver-side nodes can detect a superposition of baseband signals from multiple transmitter-side nodes, the interference can be ignored.**

Proposed physical protocol

- **If the timing of the transmission is delayed, the signal will be distorted.**
- **In wireless networks, constructive interference has not been extensively exploited because of the difficulty of achieving sufficiently accurate synchronization and requirement of highly predictable software delays.**
- **This approach is suitable for the scenarios in which the proposed scheme can be applicable (i.e., in the relay and assist phases).**



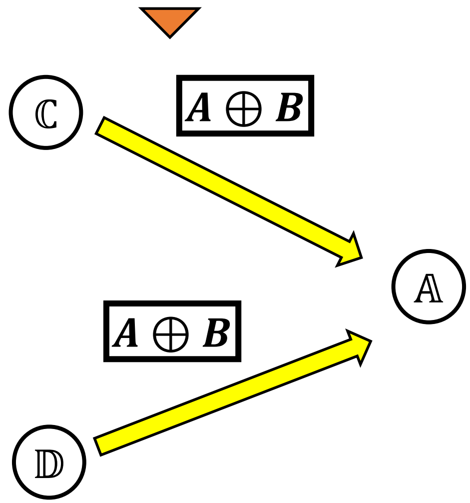
Two signals are perfectly synchronized



Two signals are slightly offset from each other

Computer simulations

- In our initial evaluation, we investigated as follows:
  - Signal restorability by using the constructive-interference phenomena
  - Improvement in data caching among nodes
- Experimental environments:
  - Experimental network is composed of a relay node, an assist node, and a receiver node, and the relay or assist node send the same data.
  - The computer simulation is conducted using the Matlab simulator.



ℂ and 𝔻 forward the NC-encoded data and 𝔸 receives them

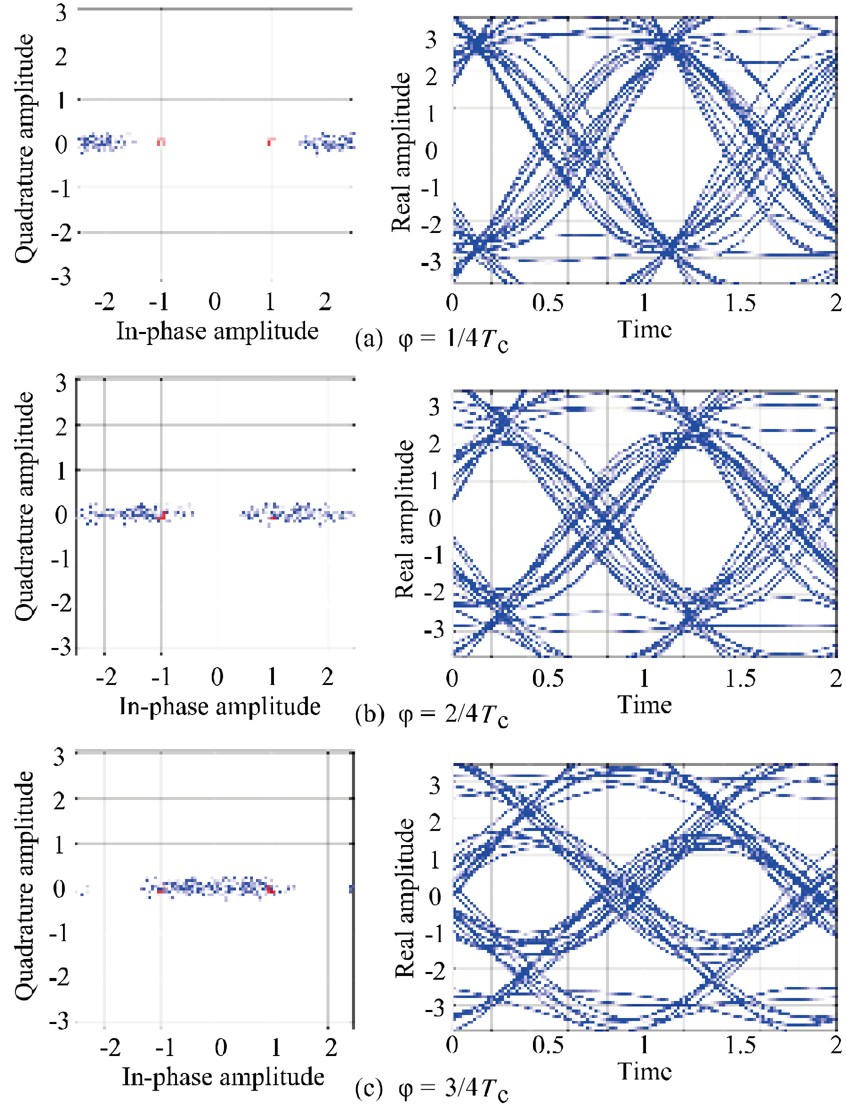
Simulation parameters

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

Computer simulations

- **Variable definitions:**
  - **The waveforms arriving from TXs has a time gap φ**
  - **Let T_C denotes the time period per one symbol in modulation**

- **Results and discussions:**
  - **The case where φ = 0 had a clearly separated constellation and a clear eye pattern.**
  - **When φ = T_C, the detector could not demodulate.**
  - **When φ = 1/4T_C, 2/4T_C, and 3/4T_C, we could achieve the separate construction and obtain a clear eye pattern, and the receiver node could correctly decode.**

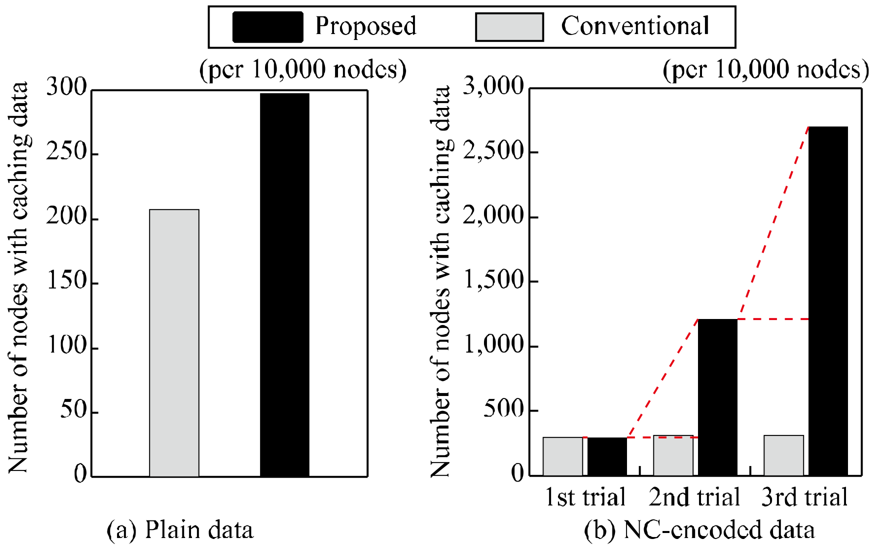


Receiver-side detector's performance, including constellation diagram and eye diagram, for received signals with a time lag.

Computer simulations

- To illustrate the benefit of the proposed assist nodes, we performed another evaluation using computer simulation implemented in C++ language.

- Simulation settings:
  - 10,000 nodes were deployed in a 1km2 area
  - Communication range: 100 m
  - Packet error ratio: 5%
  - Relay node forwards the data three times totally



Number of nodes that successfully received and cached

- Results and discussions:
  - Number of successfully cached nodes per 10,000 was improved by 43.5% thanks to the assist nodes that simply help the data forwarding
  - 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
  - Proposed scheme could cache 8.61 times as many nodes as conventional

Conclusions

- **Contributions:**
  - We 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.

- **Future works:**
  - We will expand the practical scenarios from the quality-of-service perspective to investigate long-lifetime and robustness.
  - Comparison with other schemes.

  - … many works are remained.
  - We will continue our research and development about this topics.

Acknowledgement
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Thank you for your kind attention

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