IARIA ICN 2021
@Porto, Portugal

A Fundamental Analysis of an Erase Code-enabled Data Caching Scheme for Future UAV-IC-WSNs

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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 ad-hoc networks
- Unmanned aerial vehicle-assisted wireless networks
- Wireless sensor networks
- Body area sensor networks
- Cross-layer design
- Wireless communications

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Agenda

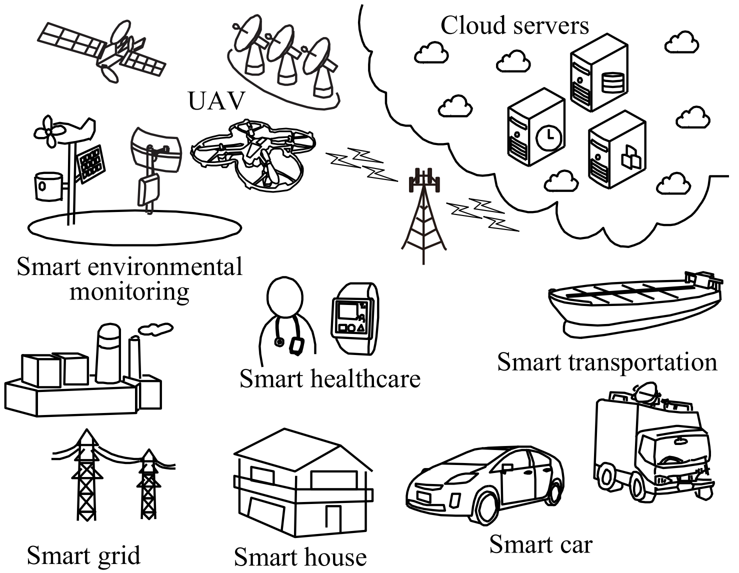
- Introduction
  - Background, motivation, and contributions
  - Information-centric network-designed WSNs
  - Unmanned aerial vehicle-assisted WSNs
- Proposed scheme
  - Overview of the proposed scheme
  - Utilization of Erase Code Technique
  - Utilization of Dual-band SN Devices
  - Proposed MAC Protocol
  - Proposed PHY Protocol
- Computer simulation
- Conclusion

Background

- Smart cities bring intelligence to various aspects of our daily lives for rapid urbanization.

- There are smart city application services, such as smart homes, personal healthcare, and urban infrastructure management.
- Smart cities alternatively include urban sophistication and resilience to serious disasters and the promotion of public healthcare during global pandemics.

- Those promises have been recognized as representative of the Internet of Things (IoT).
- Those technologies feature a diverse array of cyber-physical systems.



Example of future IoT services

Background

- In realistic cities, to facilitate decision-making and task execution, a massive number of resources, such as sensors, actuators, and data storage, need to be deployed to retain the sustainability of extensive social applications.

- The smart cities' platform should be considered in practical data management through all protocol layers.

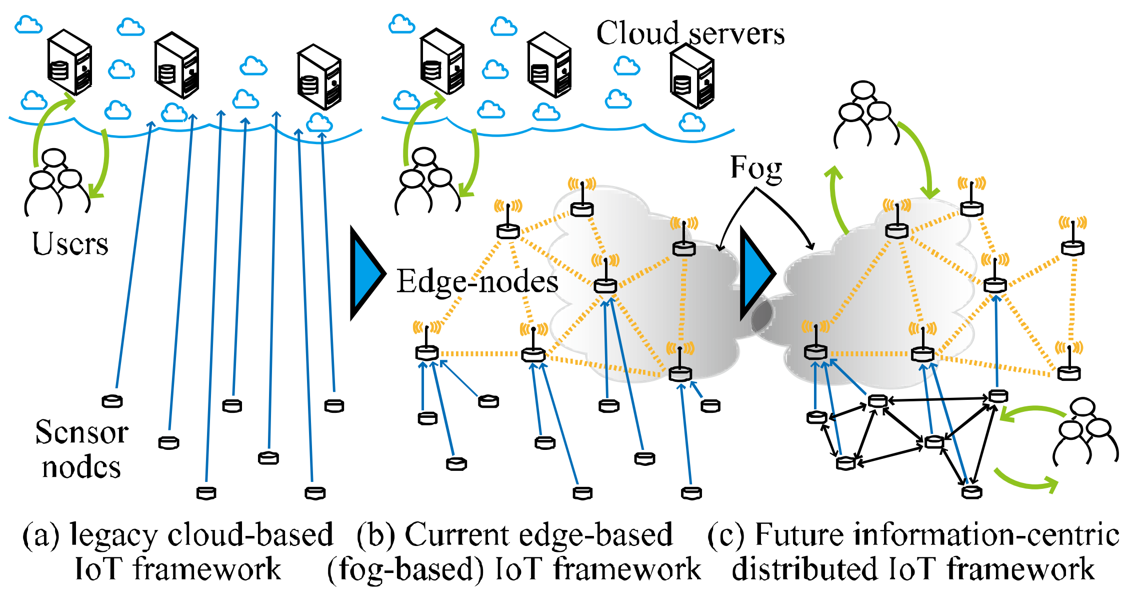
- We introduce two key technologies into our proposed scheme to realize an effective sensing data collection and management scheme for Wireless Sensor Networks (WSNs) :
  - An Information-Centric Network (ICN) design.
  - A technique for assisted data collection of Unmanned Aerial Vehicles (UAVs).

  - UAV-assisted Information-Centric WSNs (UAV-IC-WSNs)

Background

- In conventional IoT frameworks, Sensor Nodes (SNs) are directly linked to cloud servers to gather and centralize sensing data via HTTP/TCP/IP-enabled application programming interfaces (APIs).
- Typical APIs architecture is reasonable for coordinating across multiple systems.
    - Heavy address-based queries cause serious protocol overhead.

- The ICNs name content data instead of the "address."
- ICN nodes copy and store the named data as caching data for further responses.



Transition of IoT framework architecture

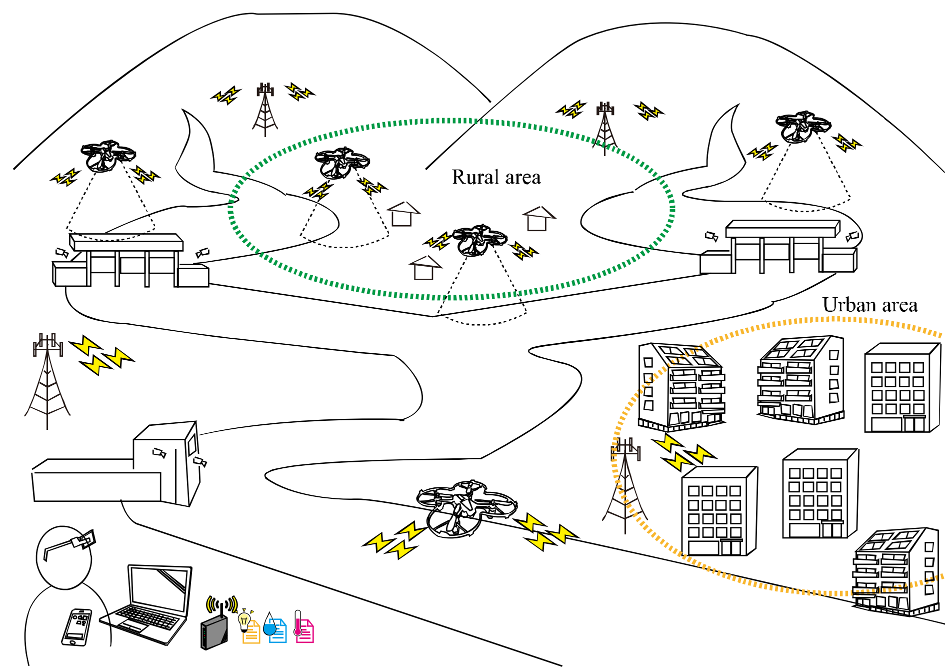
Background

- Another problem with the current systems:
- Practical SNs are non-uniformly scattered depending on the ground surface, cost-effectiveness, and need to supply.

- The sensing data are periodically generated but must be collected at asynchronous intervals.

For data collecting and forwarding

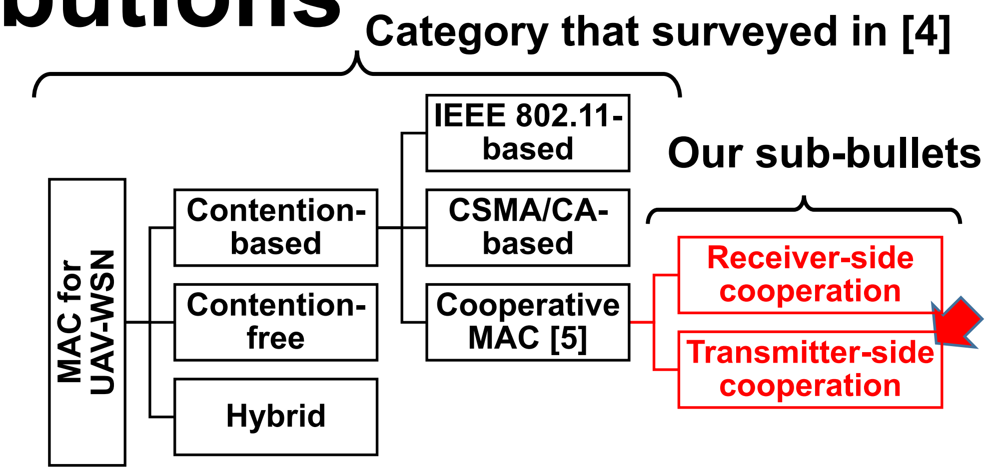
- UAVs can work more flexibly and robustly as mobile sink nodes, which play an essential role in air-ground integration networks.
- UAVs:
  - Drones
  - Small planes
  - Balloons



Overview of our target smart cities

Contributions

- We have found that our scheme cannot be used in the typical 4G/5G WSNs [3] because of heavy data traffics.



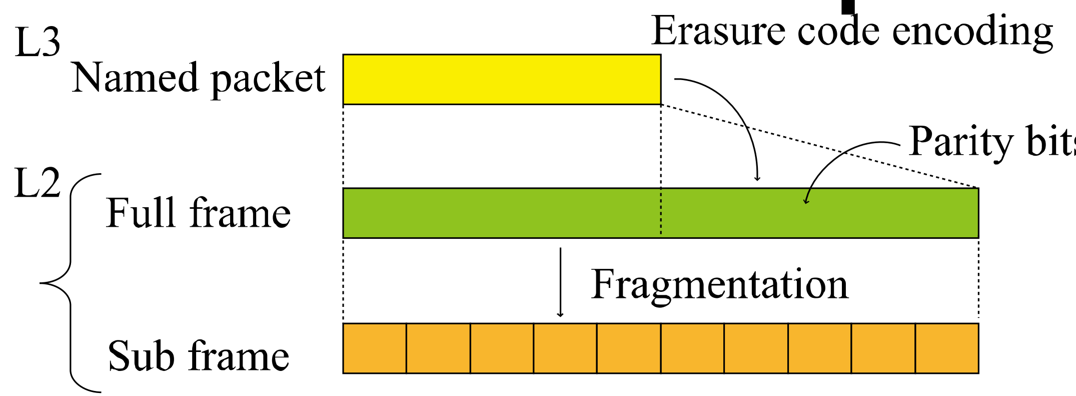
Classify of MAC protocols for UAV-WSNs

- Remained technical issues:
  - Sophisticated channel access at MAC protocol
    - We should design a novel joint sensing, forwarding, and storing scheme for transmitter-side cooperation.
    - *As the first step, we introduce an erase code technique and cross-layer optimization into UAV-IC-WSNs.*
  - Efficient radio bandwidth utilization at PHY protocol
    - *To solve the technical issues about channel capacity in UAV-IC-WSNs, we utilize dual-band SN devices.*

[3] S. Mori, "A Fundamental Analysis of Caching Data Protection Scheme using Light-weight Blockchain and Hashchain for IC-WSNs," *Proc. BRAINS 2020*, pp. 200–201, Sept. 2020.
[4] S. Poudel, et al., "MAC Protocols for UAV-Aided WSNs: A Survey," *IEEE Access*, vol. 7, pp. 65728–65744, 2019.
[5] S. Mori, "Cooperative Sensing Data Collecting Framework by using UAV in WSN," *Proc. ICC2016*, pp. 1–6, May 2016.

Utilization of Erase Code Technique

- **Error Control Code (ECC) is utilized to correct error bits at the receiver side.**
- **ECC can also be used as an erase code technique.**



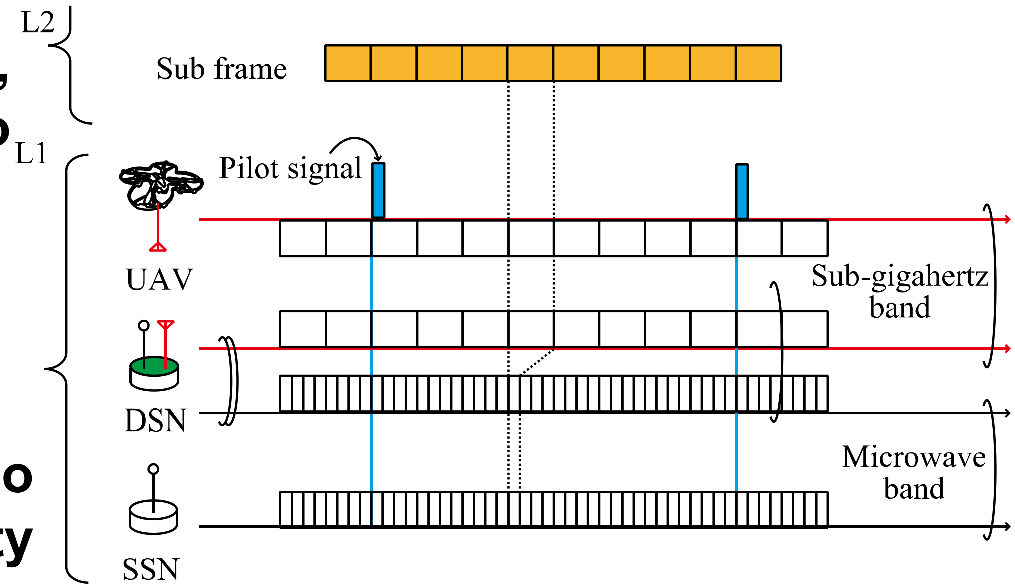
Relationship between the named packet and frame, the structure of the full-frame and sub-frame

- **Named packets are encoded based on the erase code technique, i.e., full-frame is structured by appending the parity bits.**
- **According to introducing the erase code, the original packet can be restored even if all the sub-frames are not complete.**
  - **Retransmission procedure is not necessary.**
  - **We can try to recover the original packet by fetching the lost sub-frames from the neighbor SNs.**
- **We can select ECC with Low-Density Parity-Check (LDPC) code and the Reed-Solomon (RS) code since the packets with any lost sub-frames have continuous bit errors in the sector of the lost sub-frames.**

Utilization of Dual-band SN Devices

- In the wireless air interface, our system switches to two radio frequency bands:
  - Microwave band
  - Sub-gigahertz band

Higher frequency radio leads to larger data capacity and strong straightness.



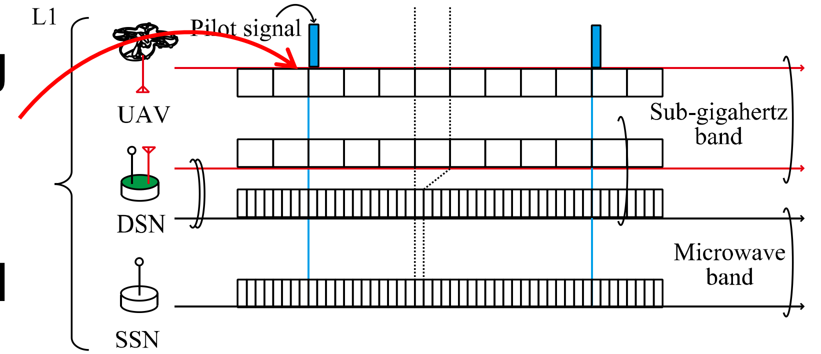
Relationship between the frame and time slot in two radio frequency bands

- Our scheme assigns the radio bands:
  - Microwave band → SN - SN
  - Sub-gigahertz band → SN-UAV

- We utilize dual bands because we suspect the familiar Low-Power Wide-Area (LPWA) networks, which typically use sub-gigahertz bands.
- LPWA will have difficulty wirelessly transmitting massive sensing data in future WSN scenarios.

Proposed MAC Protocol

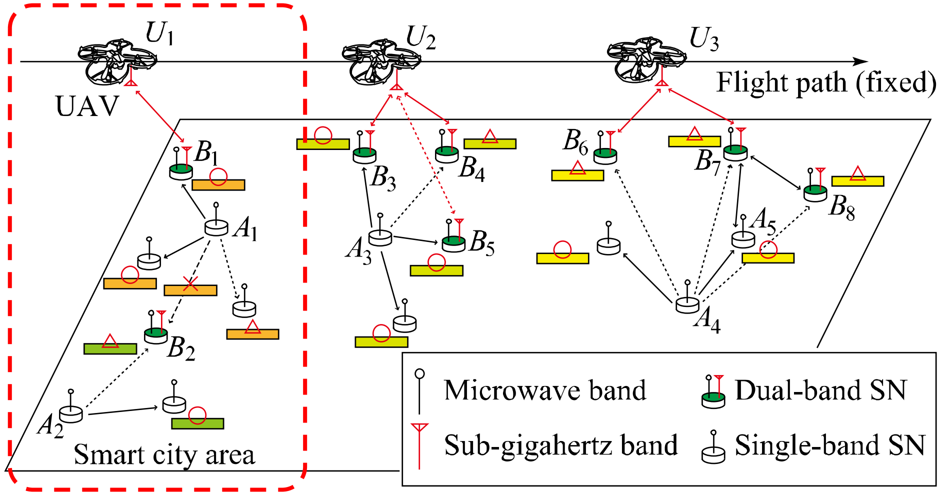
- All nodes can be synchronized using the pilot signal the UAVs broadcast.
- The MAC protocol is designed based on the slotted-ALOHA scheme.



Time slot in our MAC layer

- The wireless communication system can overhear what neighbor nodes can receive whether they desire it or not.
- For accelerating an advantage of caching scheme, the nodes should actively accumulate the overheard data (an off-path caching scheme).

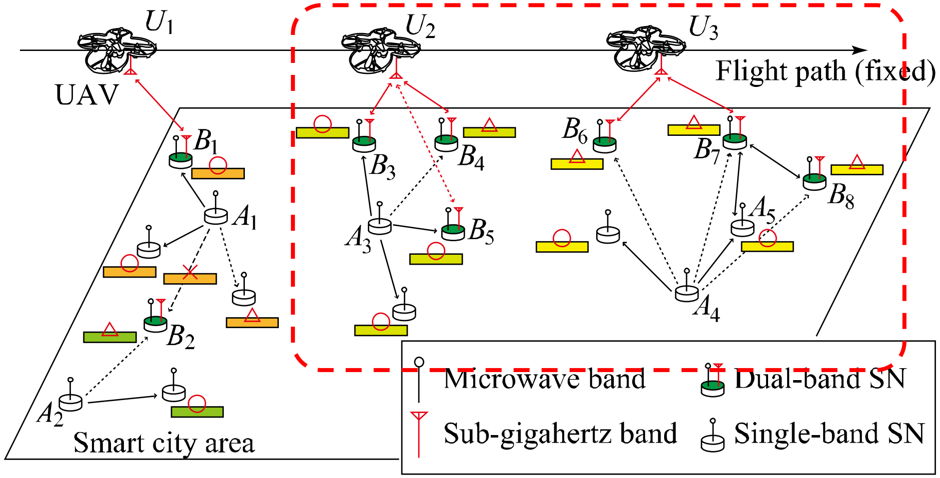
- $\mathbb{A}_1$'s data should be cached in not only $\mathbb{B}_1$ but also in neighbor SNs.
- If $\mathbb{A}_2$'s data are sent at the same time as $\mathbb{A}_2$'s, both the $\mathbb{A}_1$ and $\mathbb{A}_2$ will be interfered.
- $\mathbb{B}_2$ should be caching a part of $\mathbb{A}_2$'s data as the imperfect frame.



Procedure of our packet forwarding scheme

Proposed MAC Protocol

- **To select the dual-band SN, the UAVs give a transmission request**
- **The UAV broadcasts the interest packets to the area where the desired data might be located.**

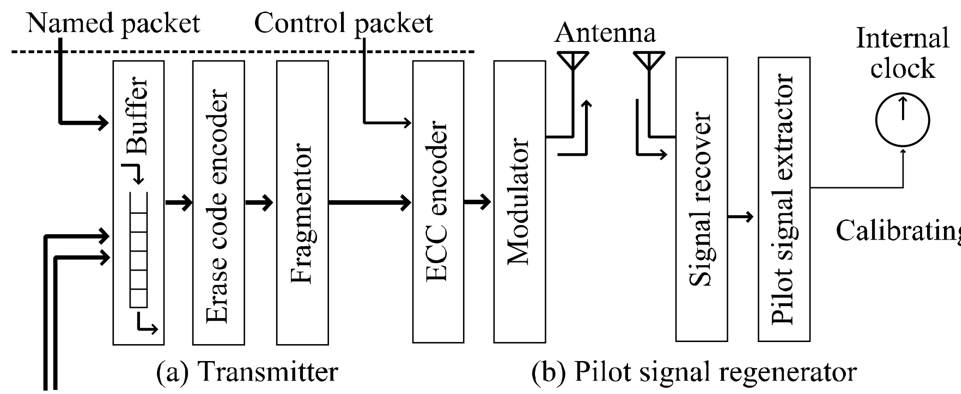


Procedure of our packet forwarding scheme

- **If one node responds to the request, the UAV can decide on it.**
  - $\mathbb{U}_1$ **selects** $\mathbb{B}_1$.
- **If there are several candidate SNs, the UAV can decide on the SN with the best wireless condition among dual-band SNs with perfect frame.**
  - $\mathbb{U}_2$ **selects** $\mathbb{B}_3$ **among** $\mathbb{B}_3$, $\mathbb{B}_4$, **and** $\mathbb{B}_5$.
- **If the candidate SNs have only imperfect data, the UAV tries to combine and restore the data**
  - $\mathbb{U}_3$ **selects and recovers both** $\mathbb{B}_6$ **and** $\mathbb{B}_7$.
- **We assume that UAV and SNs are one hop through a direct link, but multiple hops are acceptable, which is part of our future work.**

Proposed PHY Protocol

- **At the pilot signal regenerator**
  - **The synchronization signals can be restored from the UAVs in order to utilize the slotted-ALOHA scheme.**

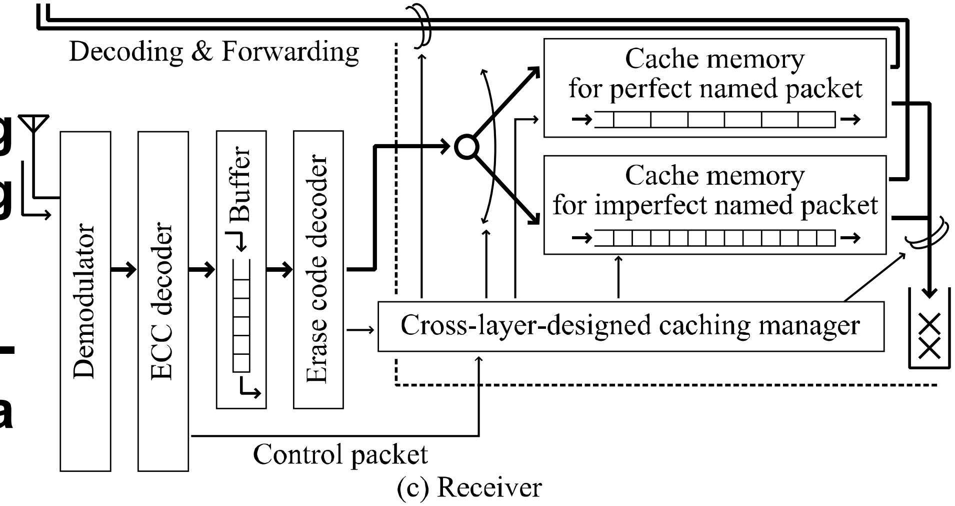


Procedure of wireless communication system

- **At the transmitter:**
  - **Full-frame is constructed at the erase code encoder by appending the parity bits that are calculated based on the named packet**
  - **Full-frame is divided into several sub-frames at the fragmentor.**
  - **Each sub-frame is encoded using ECC (that is the convolutional code) for error detection and correction through wireless links.**
  - **The codewords are mapped into the analog signals using the modulator, such as the binary phase shift keying method.**

Proposed PHY Protocol

- **At the receiver:**
  - **The received signal is decoding using the Viterbi decoding algorithm.**
  - **The correctly received sub-frames are stacked into a temporary buffer.**



Procedure of wireless communication system

- **The erase code decoder tries to recover the original packet.**
- **If the restoring process is completed, the recovered packet is stacked in the cache memory for the perfectly named packet**
- **Otherwise, the failed packet is stacked in another cache memory for the imperfectly named packet.**

- **The packets stored in those cache memories could be re-transmitted when the cooperative packet/frame transmissions are requested by other SNs and when the request is accepted.**

Computer Simulation

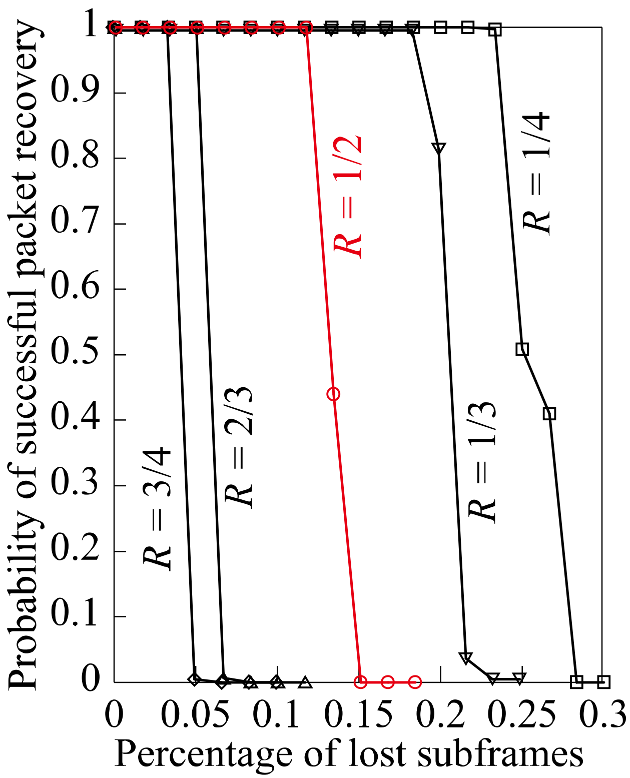
- Our initial evaluation:
  - Erase code technique's capability
  - Frame reachability via wireless channels
  - Improvement in data caching among SNs
- The LDPC code's parity-check matrix is decided based on the DVB-S2 specifications.
- We ignore the limitation of cache memory and selecting the buffered data.

Simulation parameters

Terms	Values
Erase code	LDPC with sum-products decoding
Trans. Interval	600 s (= 10 min.)
Multiple access	Slotted-ALOHA
Number of channels	15
Full-frame length	64,800 bit
Number of fragmentations	60
Modulation method	BPSK
Error control coding	Convolutional coding
Radio Frequency	2.4 GHz (in microwave), 920 MHz (in sub-GHz)
Channel model	Rayleigh fading
Radio propagation model	Erceg's model (SN-BS), Amorim's model (SN-UAV)
Transmission power	0 dBm
Antenna gain	0 dBi
Circuit loss	0 dB
Thermal noise	−172 dBm

- In Erceg's model and Amorim's model, the fading and shadowing are considered, unlike with the theoretical free-space model.

Numerical Results



(a)

- **Robustness of the LDPC-based erase code, when the code rate R is given, the original packet can be recovered:**

R	1/4	1/3	1/2	2/3
Number of lost sub-frames	11	7	3	2

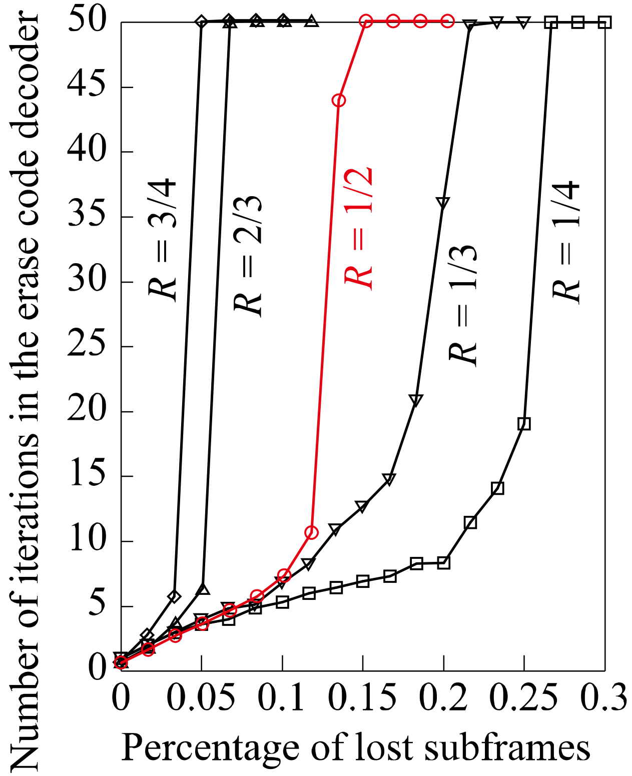
- **LDPC code has strong resilience to burst errors, but it requires a long codeword to guarantee sufficient error correction.**

We need to overcome this barrier for short sensing data message.

- **When the percentage of lost subframes is small, the curve keeps a flat shape because enough sub-frames are received.**
- **The recovery rate suddenly degraded because the received data is digitally decoded.**

There is no resistance to noise as same as an analog system.

Numerical Results

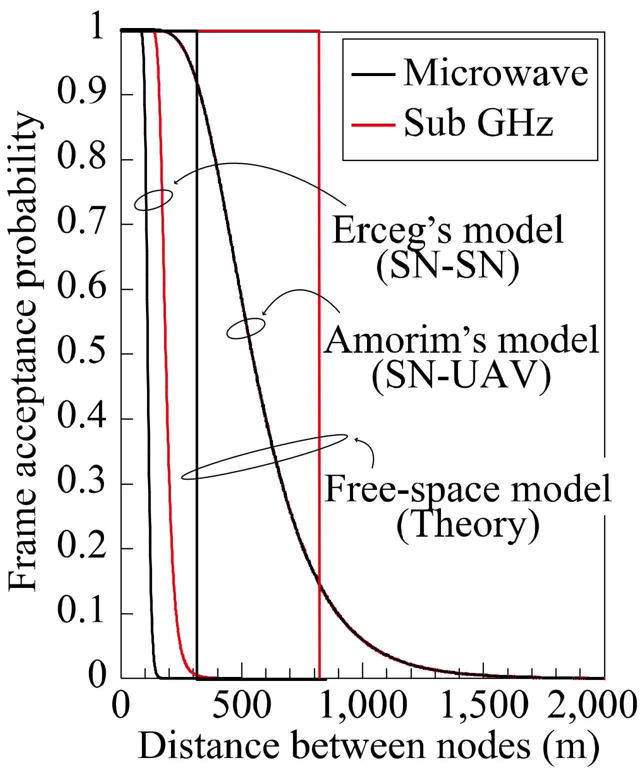


(b)

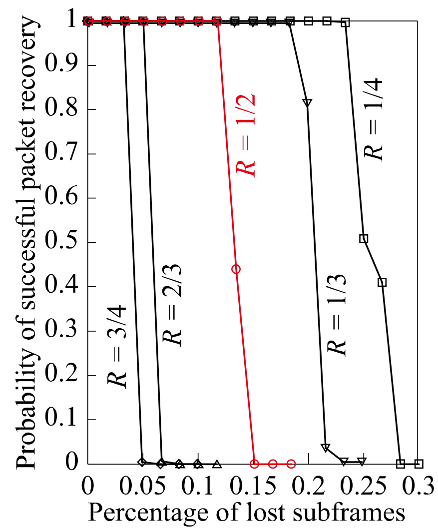
- **At the receiver side, the LDPC code decoder fulfills an iterative operation.**
  - **Sum-products algorithm**
- **Figure (b) shows the average number of iterations until a successful recovery.**
  - **Computational burden increases depending on increased iterations.**

- **The number of iterations is 10 times or less when the packet is successfully restored.**
- **Even if the number of iterative operations exceeded 50 times, no improvement occurred.**
- **The curve keeps a flat shape when the number of iterations exceeds 50 times because of reaching the upper limit.**

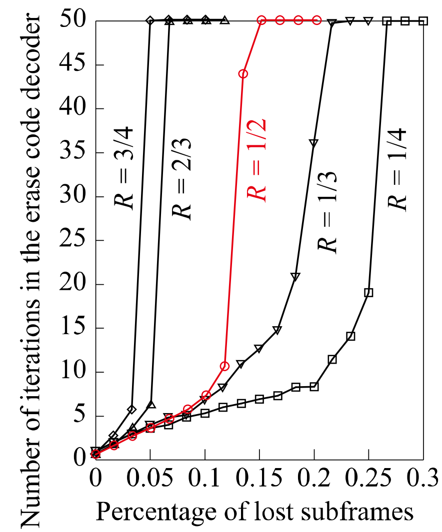
Numerical Results



(c)



(a)

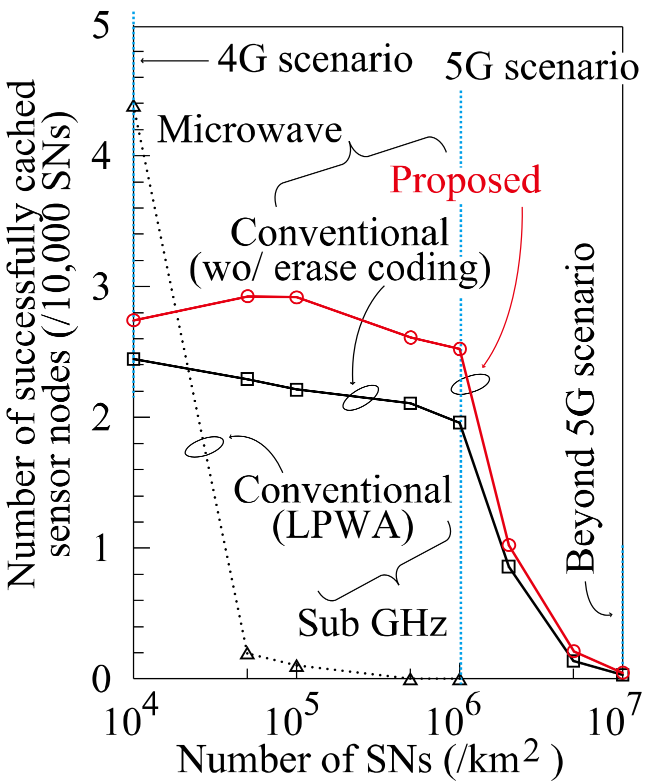


(b)

Figures (a)–(c) demonstrate the effectiveness of our scheme for packet caching

- **Figure (c) shows the frame reception probability versus the distance between nodes.**
  - **Erceg's model and Amorim's model describe smooth curves.**
  - **Amorim's model did not appear to be a difference between radio frequency bands.**

Numerical Results



(d)

- In general, number of SN deployments:
  - 10,000/km^2 (in the 4G scenario)
  - 1,000,000/km^2 (in the 5G scenario)
  - 10,000,000/km^2 (in the Beyond 5G (B5G))
- LPWA systems achieved high reachability in the 4G scenario; however, it does not work under 5G and B5G scenarios.

- Figure (d) indicates that our scheme can work under the 5G scenario by using the proposed MAC and physical protocols.
- Proposed scheme improved data caching capability by 29.3% in comparison with a comparable scheme without introducing an erase code mechanism.
- We need further analysis in our future work.

Conclusion

- **Contribution:**
  - We proposed a novel erase code-enabled data caching scheme for UAV-IC-WSNs to achieve joint sensing, forwarding, and storing.
  - We provided the overall blueprint of our proposal and a initial evaluation.
  - We reveal its fundamental features using computer simulation.

- **Future work:**
  - Feasibility for realistic environment using comprehensive simulations and hardware-based experiments.
  - Comparison with other schemes.
  - We will expand on the B5G scenarios and analyze them in practical environments.
  - It is necessary to discuss the disadvantages of dual-band SNs compared to single-band SNs in terms of power consumption and implementation cost.

  - … many works are remained.

Thank you for your kind attention