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

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Abstract—**This paper addresses an effective scheme for sensing data collection and management in future smart city applications for rapid urbanization. The main contribution of this paper provides an application of Internet of things as a new Internet technology as case study. In particular, we focus on two key technologies, an information-centric network and unmanned aerial vehicles. We propose a novel joint sensing, forwarding, and storing scheme, for which we introduce an erase code technique and cross-layer optimization. We provide the overall blueprint of our study, and we present a preliminary evaluation. The numerical results illustrate that the scheme can improve data caching capability by 29.3% in the deployment of future wireless sensor networks.**

Keywords- Information-centric network (ICN); Wireless sensor network (WSN); Unmanned aerial vehicle (UAV); Cross-layer.

I. INTRODUCTION

Smart cities bring intelligence to various aspects of our daily lives for rapid urbanization, and there are application services to realize them, such as smart homes, personal healthcare, and urban infrastructure management. In addition, smart cities alternatively include not only urban sophistication, but also 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), and they feature a diverse array of cyber-physical systems. In realistic cities, to facilitate decision making and task execution for us, a massive number of resources, such as sensors, actuators, and data storages, need to be deployed to retain the sustainability of extensive social applications. Therefore, the smart cities' platform should be considered in practical data management through all protocol layers. In our study, we concentrate on an effective sensing data collection and management scheme for Wireless Sensor Networks (WSNs) while taking into account the aforementioned background. In particular, we introduce two key technologies into our proposed scheme: an Information-Centric Network (ICN) design [1] and a technique for assisted data collection of Unmanned Aerial Vehicles (UAVs) [2], which we call the UAV-assisted Information-Centric WSNs (UAV-IC-WSNs).

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. Typical location-dependent common interfaces are reasonable for coordinating across multiple systems in distributed wireless networks; nevertheless, heavy address-based queries cause serious protocol overhead, making them similar to denial-of-service attacks. The ICNs name content data instead of the "address," and the ICN nodes copy and store the named data as caching data for further responses. Another problem with the current systems is that practical SNs are non-uniformly scattered depending on the ground surface, cost-effectiveness, and need to supply. Therefore, the sensing data are periodically generated but must be collected at asynchronous intervals. For data collecting and forwarding in those occasions, UAVs, such as drones (including multi-copters), small planes, and balloons, can work more flexibly and robustly as mobile sink nodes, which play an essential role in air-ground integration networks.

In our previous study [3], we have found that the proposed scheme cannot be used in the typical fourth-generation (4G) and fifth-generation (5G) WSN scenarios. Especially, the proposed scheme cannot accommodate into the traditional WSN system because of a huge sensing data traffic due to massive SNs. Therefore, sophisticated channel access mechanisms and efficient radio bandwidth utilization techniques must be considered as the remained works. In addition, studies on UAV-IC-WSN's Medium Access Control (MAC) protocols and physical protocols have remaining research problems [4]. Among them, in particular, acceleration in the transmission requests of sensing data leads to serious conflicts, such as collisions and interferences. In our previous study [5], we investigated a kind of cooperative MAC protocol design to remove interference among SNs, which are categorized as a cooperative sensing data collecting framework [4]. For the above atmosphere, we believe that we can overcame those technical issues by cooperative transmission, collision avoidance, and interference cancellation.

The cooperative MAC protocols can be basically classified as being either receiver-side or transmitter-side cooperation schemes. The receiver-side cooperation scheme is suitable for wireless networks to maximize their network lifetime because the rich receiver-side station nodes undertake complicated cooperative procedures. In fact, the fifth generation and beyond wireless network systems utilize UAVs as airborne base stations, and the UAV swarms provide

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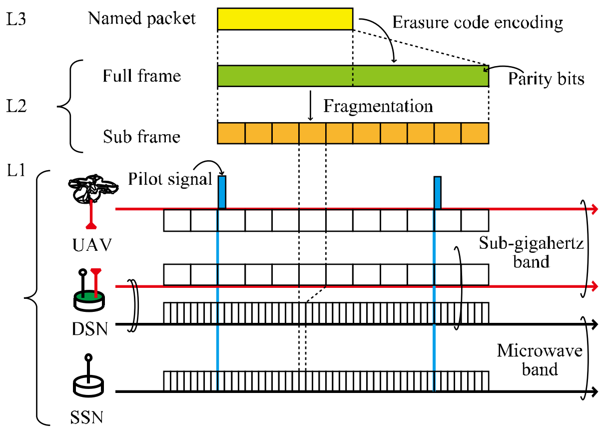

Figure 1. The relationship between the named packet and frame, the structure of the full-frame and sub-frame, and the relationship between the frame and time slot in two radio frequency bands

an integrated receiver-side cooperative reception mechanism [6]. However, we believe that cooperation at receivers is not sufficient to provide enormous sensing data transmissions. To tackle the aforementioned situation, we designed a novel joint sensing, forwarding, and storing scheme, which includes transmitter-side cooperation. To achieve the aforementioned mechanism, as the first steps, we introduce an erase code technique [7] and cross-layer optimization [8] into UAV-IC-WSNs. In this paper, we provide the overall blueprint of our study in progress, including a novel MAC and physical protocol design and a first fundamental evaluation of the scheme using a computer simulation. In particular, the key contribution of this paper is to solve the technical issues about channel capacity in UAV-IC-WSNs under 4G/5G scenarios by using dual-band SNs with erasure correction codes.

Related studies in UAV-IC-WSNs have investigated several elemental technologies. For example, Bithas et al. [9] investigated channel modeling to satisfy the requirements for massive connectivity and ultra-reliability. Li et al. [10] investigated the upper limitation of CSMA/CA-based MAC protocols and created an extended proposal. Bouhamed et al. [11] found the MAC protocols have flight path controls and trajectory optimization for UAV swarms, e.g., adaptation of machine learning techniques. As we could observe from the above literatures, there have been studied elementally wireless connectivity including antenna design and interference cancellation. Regarding an erase code technique, there have been typically studied in the field of distributed storage reliability [7]. For example, Kishani et al. [12] investigated the redundant array of independent disks. On the other hand, several studies have applied this technique in network research fields, e.g., Sharma et al. [13] utilized as an elemental technology to achieve the multipath diversity-based packet loss-tolerant network systems.

The remainder of this paper is organized as follows. Sectione II describes the proposed scheme. Section III presents the numerical results. Finally, Section IV summarizes our findings and concludes the paper.

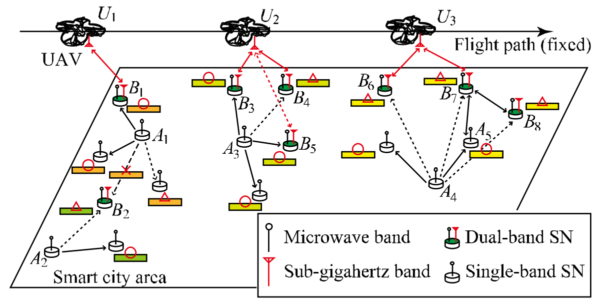

Figure 2. Network model

II. Proposed Scheme

In the UAV-IC-WSN scheme, SNs are scattered on the ground in the smart city area, and the SNs observe and cache sensing data. Then, flying UAVs collect the data as necessary. In this section, we provide a network model, the MAC protocol, and the physical protocol.

A. System Description

As shown in Figure 1, the named packet for the packet/frame format is encoded based on the erase code, i.e., the full-frame is structured by appending the parity bits. We can select among Error Control Codes (ECCs) (that is utilized as forward error correction methods) with strong resistance to burst bit errors, such as the Low-Density Parity-Check (LDPC) code and the Reed-Solomon code. This is because the packets with any lost sub-frames have continuous bit errors in the sector of the lost sub-frames. Another motivation for introducing the erase code is that the original packet can be restored even if all the sub-frames are not complete. Therefore, retransmission procedures, such as automatic repeat request methods, are not necessary when the SNs intermittently execute so as to ensure low energy consumption. Furthermore, we can try to recover the packets by fetching the lost sub-frames from the neighbor SNs.

In the wireless air interface, our system utilizes and switches to two radio frequency bands: the microwave band and the sub-gigahertz band. Note that multiband wireless communication modules were adopted in several studies [14]. In general, higher frequency radio leads to larger data capacity and strong straightness (low diffraction). Therefore, our scheme assigns the microwave band radio and sub-gigahertz band radio for the wireless transmission areas between SNs and between a UAV and SN, respectively. We proposed the utilization of those spectrum bands because we suspect the familiar Low-Power Wide-Area (LPWA) networks, which typically use sub-gigahertz bands, will have difficulty wirelessly transmitting a large number of sensing data in future WSN scenarios, which are illustrated in the numerical results.

B. Proposed MAC protocol

The MAC protocol is designed based on the slotted-ALOHA scheme because we assume that all nodes can be synchronized using the pilot signal that the UAVs broadcast.

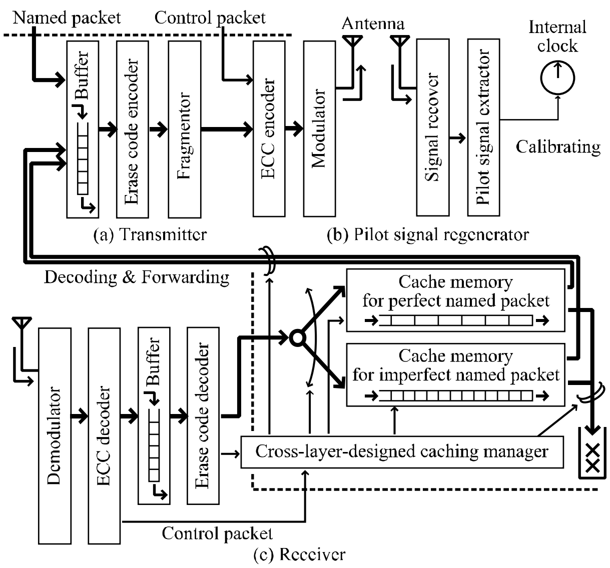

Figure 3. Procedure of wireless communication system

TABLE I. 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)
Radio transmission power	0 dBm
Antenna gain	0 dBi
Circuit loss	0 dB
Thermal noise	−172 dBm

In general, the wireless communication system has a significant feature in that it is able to overhear what neighbor nodes can receive whether they desire it or not. In our system, to accelerate the effect of the caching processing, the nodes should actively accumulate the overheard data, making it the so-called off-path caching mechanism. For example, in Figure 2, $\mathbb{A}_1$'s data should be cached in not only $\mathbb{B}_1$ but also in neighbor SNs. However, if $\mathbb{A}_2$'s data are sent at the same time as $\mathbb{A}_2$'s, the data will interfere with each other. Regardless of the circumstances, $\mathbb{B}_2$ should be caching a part of $\mathbb{A}_2$'s data as the imperfect full-frame.

To select the dual-band SN to which the UAV gives a transmission request, first, the UAV broadcasts the interest packets to the area where the desired data might be located. If one node responds to the request, the UAV can decide on it, e.g., $\mathbb{U}_1$ selects $\mathbb{B}_1$. However, if there are several candidate SNs, the UAV can decide on the SN with the best wireless condition that is obtained using the signal strength of the responding packet among the dual-band SNs that have a perfect full-frame, e.g., $\mathbb{U}_2$ selects $\mathbb{B}_3$ among $\mathbb{B}_3$, $\mathbb{B}_4$, and $\mathbb{B}_5$. Moreover, if the candidate SNs have only imperfect data, the UAV tries to combine and restore the data, e.g., $\mathbb{U}_3$ selects and recovers both $\mathbb{B}_6$ and $\mathbb{B}_7$. Note that, we assume in this paper that the wireless connection between the UAV and the dual-band SNs is one hop because the current sub-gigahertz wireless systems are typically single hop with the end devices connected to a central gateway through a direct link. However, we believe that further packet loss can be improved if multiple hops are acceptable, and this is part of our future work.

C. *Proposed physical protocol*

The signal processing of the proposed wireless communications system is illustrated in Figure 3. As shown in Figure 3 (a), the full-frame is constructed at the erase code encoder by appending the parity bits that are calculated based on the named packet; and then, the full-frame is divided into several sub-frames at the fragmentor. Each sub-frame is encoded using the Error Control Code (ECC), such as the convolutional code, for error detection and correction through wireless links. After that, the codewords are mapped into the analog signals using the modulator, such as the binary phase shift keying method. To utilize the slotted-ALOHA scheme as the multiple access mechanism, we obtain the synchronization signals from the UAVs using the pilot signal regenerator, as shown in Figure 3 (b).

At the receiver side, as shown in Figure 3 (c), the received signal is demodulated and interpreted using a method such as Viterbi decoding. The correctly received sub-frames are stacked into a temporary buffer, and the erase code decoder tries to recover the original packet using sufficient sub-frames in the temporary buffer. As a result, 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. Therefore, 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. In addition, our proposed methodology requires collaboration beyond the boundaries among the lower three layers; thus, we believe that the caching manager must be created based on the cross-layer design.

III. NUMERICAL RESULTS

Our initial evaluation of the proposed scheme included the erase code technique's capability, the frame reachability through wireless channels, and the improvement in data caching among SNs. The simulation parameters are shown in Table I. We utilized the LDPC code as the erase code, and its parity-check matrix was decided based on the DVB-S2 specifications, which are widely utilized in digital video broadcasting via telecommunications [15]. The full-frame length was decided based on the codeword length of the LDPC code, and the sub-frame length was decided based on typical LPWA systems. In this paper, to avoid system complexity, we assume that the buffer size is an ideal condition, i.e., we ignore the upper limitation of cache memory causing hardware devices, and we do not consider the selection of buffered sensing data. The radio propagation models utilized Erceg's model [16], Amorim's model [17], and the theoretical free-space model. Note that the first two models were done based on the practical measurement results, and the fading and shadowing were taken into account, unlike with the theoretical free-space model.

Regarding the robustness of the LDPC-based erase code, Figure 4 (a) shows the probability of successful recovery of the original packet if several sub-frames were lost. When the code rate R = 1/4, 1/3, 1/2, 2/3, and 3/4, the original packet could be reconstructed even if 4, 11, 7, 3, and 2 sub-frames were lost, respectively. Note that the code rate denotes the percentage of information data length in the total codeword length, including parity bits. In addition, the LDPC code has strong resilience to burst errors, but it requires a long codeword to guarantee sufficient error correction; therefore, we need to overcome this barrier for short sensing data message. In addition, in Figure 4 (a), when the percentage of lost subframes is small, the reason why the curve keeps a flat shape is enough subframes to recover a full-frame can arrive. On the other hand, the recovery rate suddenly degraded because the received data is digitally decoded; thus, there is no resistance to noise as same as an analog system.

The LDPC code decoder fulfills an iterative operation based on the belief propagation, which is called the sum-products algorithm. Figure 4 (b) shows the average number of iterations until a successful recovery, i.e., the computational burden increases depending on the increased number of iterations. As a result, the number of iterations was 10 times or less when the packet was successfully restored, and even if the number of iterative operations exceeded 50 times, no improvement occurred. In other words, in Figure 4 (b), the curve keeps flat shape when the number of iterations exceeds 50 times because the iterative decoding process reaches the pre-defined upper limitation. Note that, in Figure 4 (a) and (b), the radio propagation models are not taken into account because those simulations are performed based on lost subframes as parameters; thus, there is no effect of difference among radio propagation models. Figure 4 (c) shows the frame reception probability versus the distance between nodes. As a result, Erceg's model and Amorim's model describe smooth curves, and Amorim's model did not appear to be a difference between radio frequency bands.

Figure 4 (a)–(c) demonstrate the effectiveness of our scheme for packet caching, and Figure 4 (d) shows the computer simulation results. In general, 10,000/km^2 (in the 4G scenario), 1,000,000/km^2 (in the 5G scenario), and 10,000,000/km^2 (in the Beyond 5G (B5G) scenario) were assumed as the number of SN deployments. In Figure 4 (d), the LPWA systems achieved high reachability in the 4G scenario due to sufficient capacity for generated traffics. Therefore, the first computer simulation indicates that the proposed UAV-IC-WSNs can work under the 5G scenario by using the proposed MAC and physical protocols, while the traditional IoT frame cannot work in our previous studies. In particular, the proposed scheme improved data caching capability by 29.3% in comparison with a comparable scheme without introducing an erase code mechanism. The preliminary evaluation led us to conclude that our scheme has significant limitations for the B5G scenarios and needs further analysis.

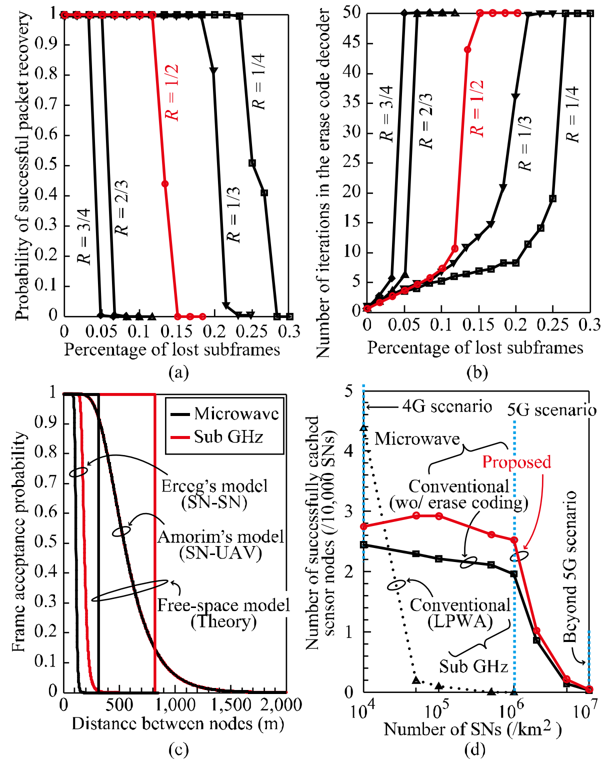

Figure 4. Simulation results: a) probability of successful packet recovery versus percentage of lost subframes, b) number of iterations in the erase code decoder versus percentage of lost subframes, c) frame acceptance probability versus distance between nodes, and d) number of successfully cached SNs versus density of distributed SNs

IV. CONCLUSION

This paper 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 fundamental evaluation. As future work, we will expand on the B5G scenarios and analyze them in practical environments. In addition, it is necessary to discuss the disadvantages of dual-band SNs compared to single-band SNs in terms of power consumption and implementation cost.

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