A Study on Delay-Sensitive Information-Centric Wireless Sensor and Actuator/Actor Networks

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***Abstract*—This paper presents an information-centric wireless sensor and actuator network for delay-sensitive applications. In particular, the delay (data freshness) metric based on the age of information is proposed. The traditional metrics in host-centric (server-client) networks are not effective because the information-centric design emphasizes content (named) data. This paper presents the blueprint of the proposed scheme and a preliminary evaluation based on computer simulations.**

Keywords*—*age of information; information-centric networking; wireless sensor and actuator/actor networks

I. INTRODUCTION

The emerging, reliable, and delay-sensitive Wireless Sensor Networks (WSNs) and Wireless Sensor and Actuator/Actor Networks (WSANs) technologies are playing an essential role in the future Internet of Things (IoT) based on wireless communications and networks for smart-city deployments, such as smart agriculture and smart industry (factories). These application services include environmental monitoring, remote sensing, and drone/robot controlling. In such scenarios, a variety of physical devices, such as temperature sensors, moisture detectors, pH sensors, and Global Positioning (Satellite) System (GPS) modules, are distributed throughout the field to gather real-time environmental data. WSANs are composed of spatially distributed controllers, sensors, and actuators communicating via wireless channels, as well as the physical processes to be controlled. In other words, WSAN is a WSN with several actuators/actors. In the spotlight on sensing data in industrial and agricultural node devices, monitoring and control data should be forwarded and processed in real time (live streaming). Then the data are collected and analyzed on a central cloud server, affecting critical tasks, such as manufacturing, product-quality management, stock monitoring, and irrigation scheduling, to improve efficiency and safety, enabling task sharing and decision-making [1][2].

For the deployment of WSNs and WSANs, the data should be exchanged reliably, delay-sensitively, and efficiently across open, autonomous, and distributed areas with minimal human involvement. In such a networking environment, Information-Centric Networking (ICN) is a promising future network architecture that shifts the networking model from host locations to transmitted information [3]. Traditional host-centric network schemes generally exchange data based on addresses, such as Internet Protocol (IP) addresses, while ICN names the data, and named data are delivered directly based on their properties (names). In some traditional networks, such as content delivery networks, data is copied and stored across network nodes, and cached data is further used for data retrieval. ICN natively enables in-network caching scheme to share data within a peer-to-peer network. Furthermore, adopting an ICN mechanism with a multi-route delivery mechanism can remove the single-route disruption failure issue and improve content delivery effectiveness. The ICN frameworks have been recently investigated in IoT platforms, which are also called Information-Centric WSNs (ICWSNs) [4]. This applies not only to WSNs but also to Information-Centric WSANs (ICWSANs).

Let us now reconsider the characteristics of WSNs versus WSANs. In Sensor Nodes (SNs), sensing data is sent via the network (an open-loop system). In contrast, in Sensor and Actuator/Actor Node (SANs), sensing (and control) data is sent, and the SAN replies with the control command data (a closed-loop system). In the study of WSANs, most research focuses on control perspective. It oversimplifies wireless network models that do not capture key parameters of a practical wireless communication system, such as latency, data rate, and reliability [5][6]. For real-time and streaming data transmissions, on the receiver-side nodes, the data must be updated promptly to ensure its freshness, as outdated data can lose its value to users and be unsuitable for actuator controls. Note that this makes WSANs more critical than WSNs because they perform critical actuator/actor controls based on the backward data from the cloud or edge-side nodes.

This paper also focuses on how delay should be considered when adopting an ICN design instead of a traditional host-centric network design. On the conventional platform, data is provided by nodes identified by their addresses; thus, the delay metric can be measured as the round-trip time using the Internet Control Message Protocol (ICMP)-compliant ping command. However, since ICN manages data by name, it does not explicitly determine which node will respond; therefore, its conventional metrics are not helpful. Note that ICN data retrieval does not necessarily require the source node to be data-providing, i.e., the data-requester-side node broadcasts a data-request (so-called interest) message to the network, and the node that stores the targeted data and closest to the requester answers.

In this study, to quantify data freshness, we propose a novel ICWSN/ICWSAN scheme that uses the Age of Information (AoI) [7] as a delay metric. The proposed scheme

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is expanding based on the previously developed ICWSN platform [8]. The contribution of this paper is to expand the AoI concept to ICWSANs, which has not been investigated in previous studies. AoI is typically defined as the time elapsed since the data is generated. For the types of related indicators, there have been slightly different definitions, such as age of synchronization (the time elapsed from when the transmitter-side node updates data until the user receives the most recent data), effective AoI (the AoI with active information updates for users), age of incorrect information (the time interval from the receiver-side node's last receipt of the most recent data from the transmitter-side node until the current time), and age of outdated information (the time difference between the current time and the time when the data at the transmitter-side node initially becomes outdated). In this paper, the blueprint of the proposed scheme is presented, including an integration of AoI for ICWSANs, its modelization, and a preliminary evaluation using computer simulations to demonstrate the effectiveness of the proposed scheme.

The remainder of this paper is organized as follows. Section II discusses related work. Section III provides a formulation of the proposed scheme. Section IV presents the numerical results and discussion. Finally, Section V concludes this paper with a summary and mention of future work.

II. RELATED WORK

Nagaraj et al. [9] investigated an industrial automation control system based on ICN and identified the requirements of industrial networks. The system focused on the application of ICN to WSANs for Industry 4.0, which aligns with this paper's direction. Zhang et al. [10] investigated a mobile edge computing system for periodically collecting data, given the limited energy and computational capabilities of node devices. The evaluation was analyzed using the AoI criterion for WSNs. Zhao [11] investigated an unmanned aerial vehicle-assisted WSNs, in which a UAV periodically collected sensing data. The evaluation of the system used an extended AoI, named the age of multi-sensor association information metric, incorporating multi-source and up- and down-link aspects for a certain type of WSANs. Huang et al. [12] investigated the trade-off between latency and reliability in packet-length control for WSANs. The author pointed out that if a message is encoded into a longer codeword, its reliability is improved at the expense of longer delay from the channel-encoding theory. Basnayaka et al. [13] analyzed a relay network with AoI for short packet communication to meet delay-sensitive requirements.

III. SYSTEM DESCRIPTION

Figure 1 shows the network model of the proposed scheme. The network structure here is the same as the ICWSN framework [8], which is extended specifically from ICWSNs to ICWSANs. The network nodes consist of Sensor Nodes (SNs), Sensor and Actuator/Actor Nodes (SANs), Relay Nodes (RNs), and Private Base Station (PBS). The SN acquires information, e.g., a sensor measurement (text-based data) or an image captured by a camera (visual data). These data include ambient noise, vibrations, and control for industrial scenarios and environmental monitoring, temperature, and humidity for agricultural scenarios. In SANs, the sensor and the actuator/actor are co-located at the same node to simplify exposition, but this need not be the case in reality. The observed data are packetized, locally processed, and prepared for transmission as sensing data, and then they are committed to the network.

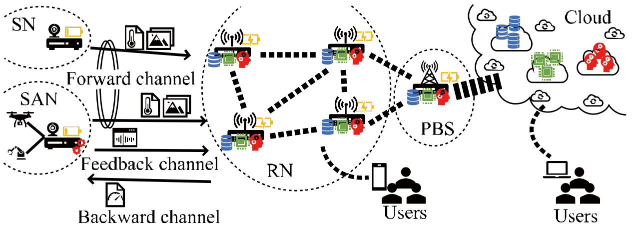


Figure 1. Network model of proposed scheme

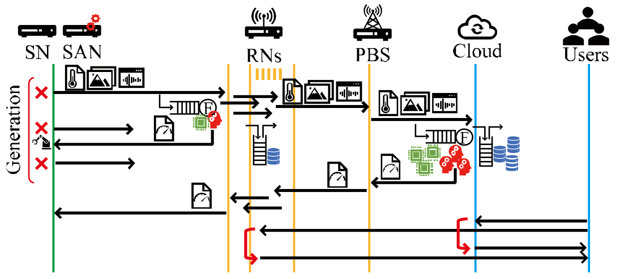
The WSAN is a distributed, closed-loop feedback control system that communicates via a shared wireless link. Therefore, in wireless links for data transmission, WSNs have only a forward channel (uplink) for sensing data, whereas WSANs additionally have a feedback channel (uplink) and a backward channel (downlink) for actuator/actor command data. Note that this paper assumes that SN and SAN can access the nearest RN with a single hop. The sensing data are forwarded to PBS, which coordinates the local area, via an edge-side network composed of multiple RNs operating as a mesh. PBS includes RN functionality and a proxy for external networks, and a portion of the sensing data is shared with the cloud if necessary. There are two types of users: internal network users and external network users. The former accesses the nearest RN and exchanges the data according to ICWSN/ICWSAN procedures, while the latter can only share and access the data and control via the cloud.

Figure 2(a) illustrates the procedure of the proposed scheme for collecting and retrieving the sensing data. To shift computational functions, such as analysis and command determination, from the cloud to the edge-side nodes, the RN is equipped with a functor (and a queue). SNs and SANs periodically generate data and send it to the nearest RN. In particular, SANs' data is sent to RN, PBS, and cloud servers, and feedback data is sent back to control the systems appropriately. In contrast, the sensing data are retrieved by users as needed. The user commits a data retrieval request (interest) to the network, and the data delivery is completed when the nearest node that holds the requested data returns a response. In this case, the data freshness is modeled as follows.

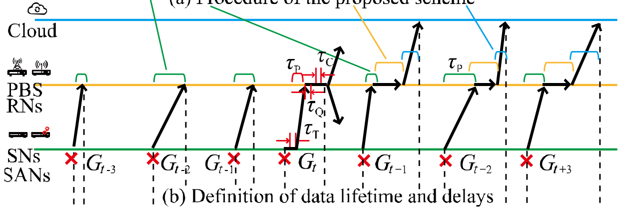
Supposing K SNs/SANs are distributed in an ICWSN or ICWSAN field. The n th SN/SAN ($n = 1,2,\cdots,N$) sends the sensing data periodically, which is given by

$$x_{t+1,n} = ax_{t,n} + bu_{t,n} + w_{t,n} \tag{1}$$

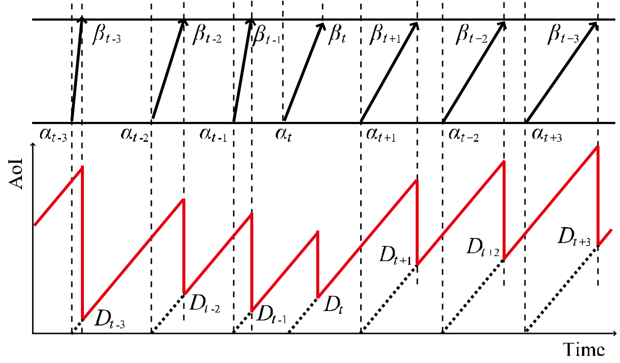
where $x_{t,n}$ is the sensing data via the forward and feedback channels, $u_{t,n}$ is the control data via the backward channel, and $w_{t,n}$ is the (thermal and ambient) noise in the device and channel at time t. a and b are constant values that depend on the environment and device.



(a) Procedure of the proposed scheme



(b) Definition of data lifetime and delays



(c) Definition of age of information (AoI)

Figure 2. Prodecure of proposed scheme and definition of AoI metrics

The AoI is a time-dependent metric; in other words, delays carry a significant weight. As shown in Figure 2(b), four delays are considered: transmission delay propagation delay, caching (queuing) delay, and calculation delay. Transmission delay, τ_{T}, occurs when the transmitter-side node generates data and converts it into packet, including packetizing (framing), both source and channel coding, and modulation over the air interface and via the network system. Propagation delay, τ_{P}, is the time interval for wireless transmission, which is primarily dominated by the distance between SN/SAN and RN/PBS, and radio-link conditions. Caching delay, τ_{Q}, occurs due to network congestion and significant queueing delays related to the network operations, such as routing, switching, and protocol processing. Calculation delay, τ_{C}, arises during computational calculations in the functors, depending on the hardware and software implementations.

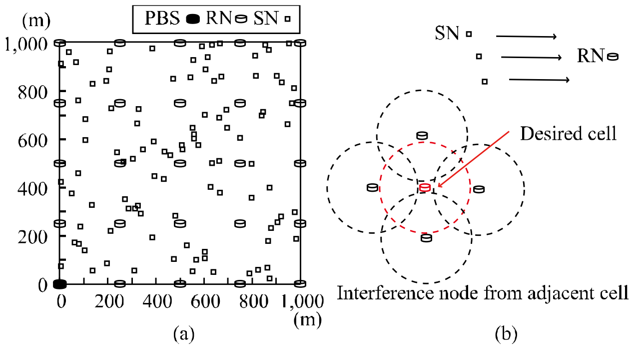
As shown in Figure 2(b), let G_t denotes the generative function of the data in any k-th SN/SAN; therefore, the AoI is expressed as shown in Figure 2(c). Namely, for any k-th SN/SAN (i.e., the subscription of k is ignored for simplicity), let α_t and β_t denote the timestamp of the data generation and reception at t, respectively. Note that we can rewrite $G_t = \alpha_t - \alpha_{t-1}$. Letting $\ell(t) \triangleq \beta_t - \alpha_t$ denotes the freshness of the most recently updated data; hence, the AoI at the time t can be expressed as

$$\Delta(t) = t - \ell(t) \tag{2}$$

where $\ell(t)$ for the link between SN/SAN and RN can be rewritten on the basis of the previously defined latencies as

$$\ell(t) = \tau_{\mathrm{T}} + \tau_{\mathrm{P}} + \tau_{\mathrm{Q}} + \tau_{\mathrm{C}} \tag{3}$$

and for the wireless link between SN/SAN and PBS, i.e., under multi-hop conditions, $\ell(t)$ can be calculated multiplying (3) by the number of hops, but each delay depends on the individual nodes and wireless communication channels. In practical aspects, ℓ can be calculated from the timestamp recorded in the named data and the current time, under assuming the local time on the network nodes is synchronized.



(a)

(b)

Figure 3. Simulation environment

TABLE I. SIMULATION PARAMETERS

Terms		*Values*
Size of observation field in ICWSN/ICWSAN		1 km^2
Number of SNs, N		10,000 /km^2
Number of RNs (including a PBS), K		25
Number of chennels	Microwave-band link	24
	mmWave-band link	108
Coverage range		200 m
Delay	Transmission τ_{T}	300 ms per data
	Propagation τ_{P}	500 ms per hop
	Caching (queuing) τ_{Q}	100 ms per data
	Calculation τ_{C}	1,000 ms per data

IV. NUMERICAL RESULTS

This section provides a preliminary evaluation of the ICWSN/ICWSAN system with AoI based on the ICWSN platform [8] and the ICWSAN platform [14]. The computer simulations include ICN's cache functionality, functors, queues, and wireless communication. Figure 3 shows the simulation environment, and Table I listed the simulation parameters. As shown in Figure 3(a), the SNs were randomly deployed across a 1-km^2 field, and the RNs are placed in a rectangular lattice pattern. The wireless link between SN and RN was assumed to use microwave-band radio with single-hop transmission, and the links between RN and RN (or PBS) were assumed to use millimeter-wave (mmWave)-band radio with multi-hop transmissions. The number of wireless channels was determined based on Wireless Local Area

Networks (WLANs), i.e., IEEE 802.11 standard (see Table I). Namely, in microwave bands, such as 2.4/5-GHz WANs, the bandwidth per channel is 20 MHz and the number of channels is counted fully independent spectrum without overlapping. While, in mmWaves, IEEE 802.11 ad/ay-compliant WLANs is assumed, and it generally assigns four 2.16-GHz-bandwidth channels in the 60 GHz band. Therefore, the number of channels was calculated based on the spectrum allocated to the mmWaves, at the same channel bandwidth in the microWaves.

To simplify the simulations, the delay parameters were set to constant values, and further in-depth investigation remains a task for the future. Nemaly, the routing path for ICWSN and ICWSAN was predefined and fixed. The data, such as named data, packets, and frames, were assumed to be fixed in size. The source and channel coding method and the modulation and demodulation scheme were worked under the same conditions. The channel conditions remained stable (unchanged), i.e., no retransmissions occurred within the coverage area. The data processing for the individual data was performed under the same conditions, with the same computer performance on the network nodes. Furthermore, the size of cache memories (storage) on the network nodes was unlimited, i.e., the data was not lost due to overflow. Since the proposed AoI metric is significantly depending on the interval between the data generation and reception, the accurate clock synchronization across network nodes is essential for its correct operation. The paper assumes that time synchronization among nodes is consistently maintained; practically, a periodic time synchronization using GPS or Network Time Protocol (NTP) technique is feasible and required. In addition, this simplification may be acceptable for propagation, transmission, and computation delays, but it is problematic in the case of queuing delays. Therefore, the effect of the proposed metric in an actual network environment remains an ongoing consideration.

Figures 4–6 show the simulation results. Figure 4 shows the Cumulative Distribution Function (CDF) of the number of SNs accommodated in an RN. As a result, the number of SNs per RN was unbalanced, and the minimum was 117, the maximum was 718, the average was 400, and the median was 322, respectively. In practice, the distribution of SNs is also non-uniform, so the results are expected to be even more biased. Here, for simplicity, we assumed that an RN contains 400 SNs. Figure 5 shows the channel occupancy rate, average number of lost data, and average data size accumulated in the receiver-side buffer versus the interval between data generations (without interference) and the number of interference nodes (corresponding to one to four neighborhood RNs), as shown in Figure 3(b). Given a data generation interval of 30 s or longer and no interference nodes, the system can handle the data without packet loss or buffer overflow. Note that this simulation assumes an unlimited buffer capacity for simplicity, but in practice, buffers typically have upper limits, and the overflow can cause data loss. As shown in Figures 5(a) and (b), for generation intervals of 30 s and 60 s, even with an interference node present (up to four neighboring cells), the results showed that the system worked properly with a 60-s interval, whereas it was completely ineffective with a 30-s interval. As shown in Figure 5(c), the

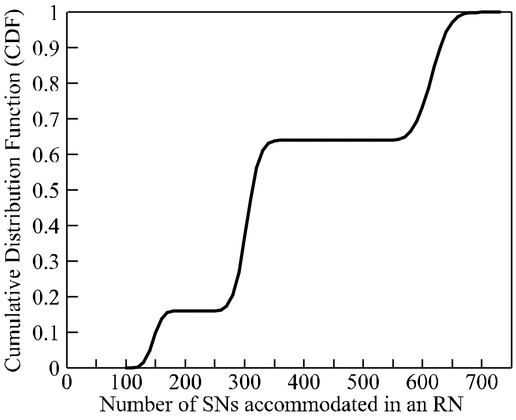


Figure 4. CDF versus number of SNs accommodated in RN

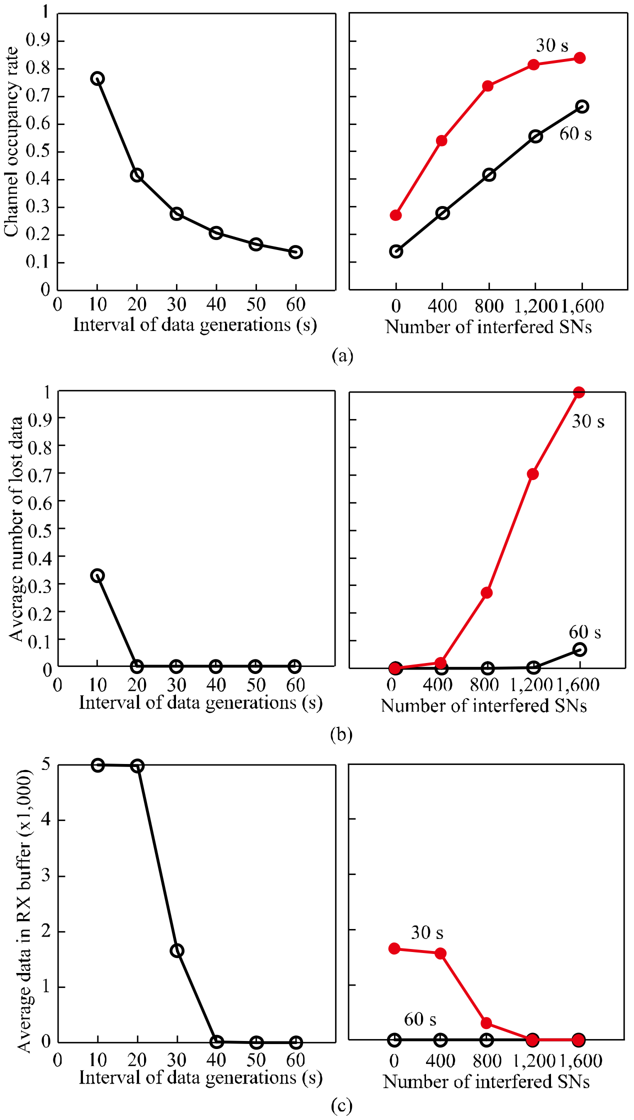


Figure 5. Channel occupancy rate, average number of lost data, and average data size accumulated in receiver-side buffer versus data-generation interval and number of interferenced nodes

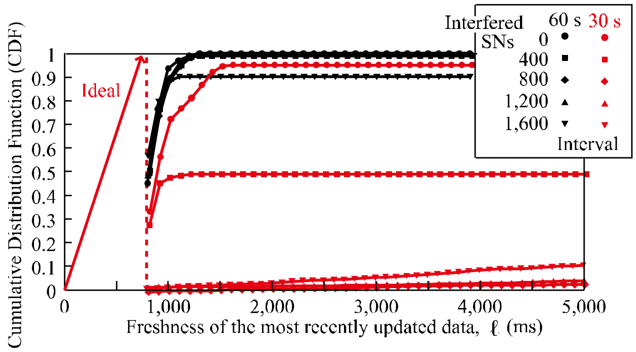


Figure 6. CDF versus freshness of most recently updated data

receive buffer is improved when the amount of generated data increases, i.e., the interval and interfered nodes were increased, because the buffer is overflowed and then the data cannot reach the receiver-side node.

Figure 6 shows the CDF versus the freshness of the most recently updated data, ℓ, as a numerical example directly related to AoI. Under ideal conditions, the delay would be 800 ms as represented by the arrow in the figure. However, due to the wireless channel, the receiver-side buffer, and interference from neighbor nodes, the arrival time (β) was delayed, resulting in a larger ℓ. For 60-s intervals, the data arrives within 1,500 ms, even with interference from neighbors. Based on these numerical results, the constant parameters should be determined to ensure that AoI-based data freshness is appropriately performed depending on the network scale, which is a future study and ongoing work.

V. CONCLUSION AND FUTURE WORK

This paper proposed to introduce an AoI-based metric to the ICWSAN system as an essential delay indicator for delay-sensitive applications and provided a preliminary evaluation. As a future work, more detailed simulations and evaluations should be conducted.

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