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Effectiveness-Oriented SAGSIN: Unveiling a Unified Metric and a Comprehensive Framework

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***Abstract*—The space-air-ground-sea integrated network (SAGSIN) has emerged as a consensus from both industry and academia to provide seamless coverage and ubiquitous connectivity in the upcoming sixth generation networks, which can facilitate various remote mission-critical applications. However, the quality of service (QoS) satisfaction of mission-critical applications is significantly undermined by the adverse impacts resulting from the inherent characteristics of SAGSIN, including large scale, high dynamics, low computing and caching capability, and limited perception and communication. These characteristics severely deteriorate the timeliness and ultimate effectiveness performances of mission-critical applications in SAGSIN. In this article, we present an *effectiveness-oriented* SAGSIN which lays particular emphasis on the timeliness/effectiveness performance in order to ensure QoS demands of mission-critical applications. We review classic performance metrics, and then propose a new metric, named *synchronization cost of information* (SCoI) that directly describes the effectiveness of mission-critical applications. To effectively support mission-critical applications, we propose a joint perception-communication-computing-actuation (JPCCA) framework that adapts to the time-varying network environment. A case study on object detection and tracking in SAGSIN demonstrates the superiority of the proposed metric and framework as compared to baseline schemes. Finally, we point out the open issues on effectiveness-oriented SAGSIN implementation.**

***Index Terms*—space-air-ground-sea integrated network (SAGSIN), synchronization cost of information (SCoI), mission-critical applications, joint perception-communication-computing-actuation (JPCCA).**

I. INTRODUCTION

The sixth generation (6G) networks are expected to provide ubiquitous communications with high reliability and low latency, supporting seamless and timely connections at any place and at any time [1]. Nevertheless, approximately 71% of the area of Earth surface is covered by the sea and 20% by the desert and forest, where terrestrial networks cannot provide continuous connections due to the limitation of high-cost ground infrastructures. To achieve seamless coverage in these areas, the Space-Air-Ground-Sea Integrated Network (SAGSIN) [2] that integrates the disjoint network segments has been proposed to facilitate ubiquitous communication services.

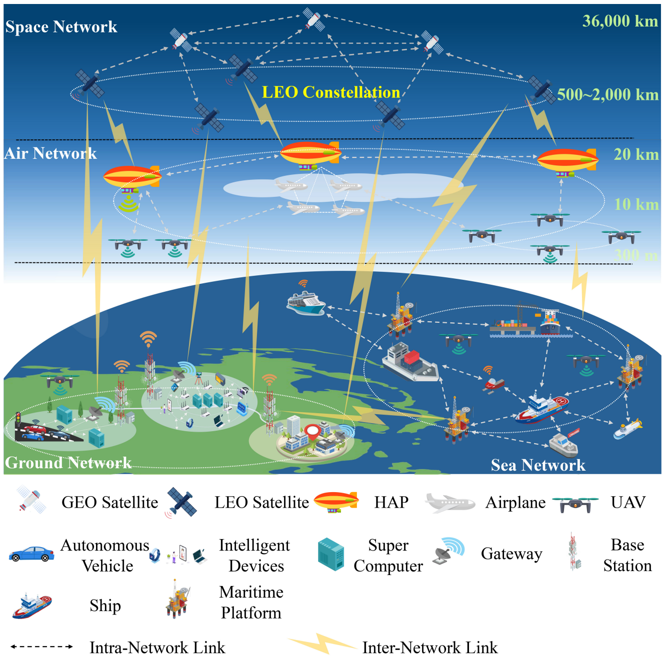

Fig. 1. The architecture of SAGSIN.

As shown in Figure 1, the SAGSIN is composed of four components:

- Ground network, including terrestrial nodes such as autonomous vehicles and ground base stations/gateways.
- Air network, including aerial nodes such as unmanned autonomous vehicles (UAVs), airplanes, and high-altitude platforms (HAPs).
- Space network, including space nodes such as low earth orbit (LEO) satellites/constellations and geostationary earth orbit (GEO) satellites.
- Sea network, including marine nodes such as ships and marine platforms.

By connecting the nodes in each SAGSIN components via intra-network links, and then integrating these four distributed components via inter-network links, the SAGSIN can

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support considerably long distance communications. Thus, a great quantity of remote *mission-critical applications*, such as real-time status monitoring, emergency response, remote distributed learning, and remote control, can be facilitated by utilizing SAGSIN that provides satellite/HAP relays along with heterogeneous resources. These applications significantly extend the concept of 6G communications and remark a leap from fifth generation communications.

These mission-critical applications have stringent requirements for *timeliness*, as fresher messages can better facilitate accurate estimation and precise decision-making at receiver side. Therefore, reviewing existing timeliness metric, including age of information (AoI) [3], nonlinear AoI [4], age of incorrect information (AoII) [5], and urgency of information (UoI) [6], is significant in describing timeliness performance. However, in terms of capturing the *ultimate effectiveness* yielded by mission-critical applications, refinements of timeliness metric, which are effectiveness metrics, should be further discussed. Refining timeliness metrics to be *effectiveness-oriented* is vital to describe the effect of terminal actuation in mission-critical applications, ensuring higher quality of service (QoS). Furthermore, given the inherent characteristics of SAGSIN, including large-scale, high dynamics, low computing and caching capability, and limited perception and communication, refining conventional measures and communication paradigms is imperative to better fit with these characteristics. This presents a positive opportunity to develop unified metric and high-level communication framework that describe and optimize effectiveness-oriented QoS.

In this article, aiming at enhancing effectiveness, we propose an *effectiveness-oriented* SAGSIN to ensure high QoS of mission-critical applications. We propose a new unified effectiveness metric called synchronization cost of information (SCoI) to describe the effectiveness-related QoS, namely the influence of actuation, in mission-critical applications. Moreover, different from previous works that focus on the joint sensing-communication-computing framework [7] or significance-oriented (which is equivalent to "effectiveness-oriented" in this article) joint perception-communication-control framework [8], an intelligent effectiveness-oriented closed-loop joint perception-communication-computing-actuation (JPCCA) framework is proposed. By utilizing artificial-intelligence-based (AI-based) technologies, the perception, communication, and actuation techniques can jointly capture and adjust to the variable environment status, and the ultimate effectiveness can thus be guaranteed. The proposed SCoI and JPCCA framework can serve as metric and paradigm of third-level effectiveness communications [9]. We finally present some future challenges on the design of effectiveness-oriented SAGSIN.

The contributions of this article are summarized as follows:

- We propose a new metric called SCoI to refine existing timeliness metrics as effectiveness-aware. SCoI reflects both status estimation cost and ultimate actuation cost of messages and thus demonstrates the effectiveness of information.
- We propose the JPCCA framework to jointly design the perception, communication, computing, and actuation techniques involved in the closed-loop information flow. By a co-design approach of these techniques, the ultimate effectiveness is enhanced via module interaction and collaboration.
- We showcase the effectiveness gain of the proposed JPCCA design by study on the UAV-based object detection and tracking task. Simulation results show that the SCoI-optimal scheme outperforms baseline schemes in terms of task execution time and transmission overhead.

The rest of the article is organized as follows: Section II elaborates on the characteristics and application scenarios of the SAGSIN. In Section III, we review existing timeliness metrics and propose SCoI. Section IV introduces the architecture of JPCCA framework. A case study on effectiveness-oriented UAV-based object tracking is conducted in Section V. Then, we point out several open research issues of effectiveness-oriented SAGSIN implementation in Section VI, and Section VII conclude the article.

II. CHARACTERISTICS AND APPLICATION SCENARIOS OF SAGSIN

In this section, we firstly elaborate on four inherent characteristics of SAGSIN and explain the challenges of effectiveness-oriented SAGSIN. Then, we present several typical mission-critical application scenarios that can be facilitated by SAGSIN.

A. Characteristics of SAGSIN

The following inherent characteristics of SAGSIN challenges the timeliness and effectiveness of mission-critical applications:

Large scale: Large-scale communications make it difficult to realize high-timeliness due to long propagation delay. For example, LEO satellites have an altitude of 500-2,000 km, causing approximately 17-67 ms one-hop propagation delay; GEO satellites are at an altitude of about 36,000 km, resulting in around 120 ms one-hop propagation delay. Moreover, considering multi-hop communication where direct connection cannot be satisfied, the propagation delay along with relaying delay will accumulate to beyond one second. The large latency between message generation and its acknowledgment will decrease timeliness of information and thus the effectiveness of tasks.

High dynamics: Highly dynamic environment of SAGSIN severely challenges the high timeliness and effectiveness of communication. Specifically, in space-sea communications, the high mobility of satellites results in short service time, and natural factors such as atmospheric attenuation and cosmic ray cause low signal-to-noise ratio (SNR), both decreasing the QoS. Furthermore, the Doppler shift originating from high mobility will also affect the channel condition. For instance, an LEO with 750 km orbit altitude and 100 minutes period will cause several hundred kilohertz Doppler shift, which is not negligible compared to bandwidth (about tens of megahertz). The above dynamic factors will decrease the transmission accuracy and reduce the effectiveness of tasks facilitated by SAGSIN.

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Low computation and caching capability: Realizing high effectiveness in SAGSIN is significantly difficult due to low computing and caching capabilities of SAGSIN. Specifically, the typical terrestrial central processing units (CPUs) are with 275 tera operations per second (TOPS) of computation speed, while this value for satellite CPUs is only tens of TOPS. Moreover, UAVs and satellites encounter limitations in terms of storage capacity, since their typical memory sizes are 8 and 300 gigabytes. These sizes are significantly smaller as compared to ground computers which typically install two terabytes hard drives. Low computing and caching capabilities decrease the speed of intelligently conducting mission-critical applications and thus lower the effectiveness.

Limited perception and communication: Restriction of perception and communication resources in SAGSIN also compounds the issue of low timeliness and effectiveness. For instance, the typical sensing angle of view for remote sensing satellites is between 10° and 60°, and the spacial resolution is approximately one meter. As comparison, terrestrial security cameras have approximately 100° angle of view and tens of centimeters spatial resolution. As another example, 3GPP suggests that the bandwidth of uplink and downlink satellite communication be 400 megahertz [10], which is still way behind ground networks with one gigahertz maximum bandwidth. The characteristic of limited resources makes it challenging to acquire the information effectively at the transmitter side, inexorably affecting the effectiveness of SAGSIN.

B. Application Scenarios of SAGSIN

In this subsection, we present four typical mission-critical application scenarios that demand stringent requirements for high levels of timeliness/effectiveness.

Real-time status monitoring: Real-time status monitoring plays a vital role in real-time observation/detection services such as maritime spectrum situation awareness and ship detecting, which rely greatly on SAGSIN because the observing area is so large that ground network cannot provide timely and continuous services. Specifically, monitors continuously capture the multi-modal data, including images, temperatures, and spectra, from the observing area for sequential transmission. Nevertheless, the difficulty in processing multi-modal data challenges the effective actuation of observation/detection services. The issue of multi-modal data processing can be tackled by introducing AI-based learning techniques to extract the semantics of messages and compress the original data, which will be discussed in Section IV-A.

Emergency response and rescue: In case of emergency on open sea or deep inland where terrestrial networks cannot provide communication services, SAGSIN is imperative to compensate for lack of coverage and provide timely access to communication resources. Specifically, in maritime rescue tasks, sensors on the maritime platforms continuously monitor the environment statuses, and transmit emergency messages when detecting abnormal statuses. Due to limited bandwidth and long communication distance, we should resort to SAGSIN which can transmit the emergency messages via satellite/HAP relay system. Nevertheless, the long-distance and multi-hop communications may cause collision and transmission failure. To overcome these issues and thus achieve high effectiveness, AI-based transmission scheme design can be utilized, which will be detailed in Section IV-B.

Remote distributed learning: In the SAGSIN, the aforementioned AI-based observation/detection and communication services involve extensive distributed learning, which requires for higher computing speed, greater caching sizes, and larger memories. Along with the huge enhancement of super computers, the remote distributed deep learning (DL) services can be offloaded to the edge/cloud servers with faster computing speed and more computing resources. For instance, in UAV-based object detection tasks, the computing and caching resources of UAV are limited which only support training on few of captured images. Utilizing the SAGSIN, most of training tasks can be offloaded to the edge/cloud servers. The cloud/edge computing resources need to be intelligently allocated to guarantee high-effectiveness, which will be elaborated in Section IV-C.

Remote control and operation: With the unprecedented development of wireless network control systems (WNCS), delay-sensitive services such as remote autonomous driving and surgery have emerged rapidly because of LEO/HAP relays provided by SAGSIN. Specifically, remote nodes monitor the status in certain areas and send the monitored messages to the control center, and the center generates and transmits corresponding control commands back according to received messages. Remote nodes then operate correspondingly based on the commands. Nevertheless, the message processing and the command generation are affected by highly dynamic environments, which results in low preciseness of generated commands and thus reduces effectiveness of tasks. To cope with the time-varying aspects of the environment, AI-based WNCS is required to intelligently capture the variation and generate adaptive commands, which is the subject of Section IV-D.

III. PERFORMANCE METRICS

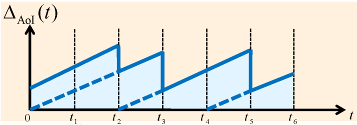
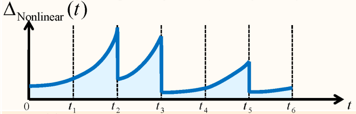
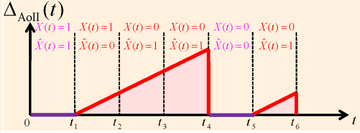
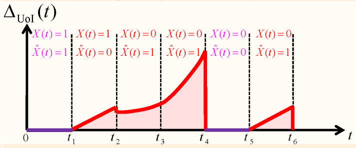
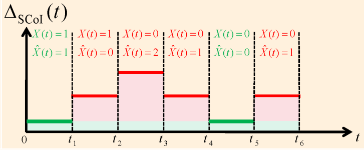
In this section, we first review the existing timeliness metrics, including AoI, nonlinear AoI, AoII, and UoI, which describe the QoS performance of mission-critical applications in the SAGSIN. We then propose a new performance metric called SCoI that captures effectiveness by describing both actuation costs and status estimation costs of information.

A. Existing Timeliness Metrics

(1) **AoI:** AoI is a crucial metric that measures the time elapsed since the latest successfully acknowledged message is generated [3] (refer to Table I). AoI captures the timeliness of the status update system by assigning a linearly increasing age cost. However, recognizing the diverse needs of practical applications, particularly in mission-critical applications, there arises an opportunity for AoI variants by introducing more flexible nonlinear cost functions.

(2) **Variants of AoI:** The nonlinear AoI introduces a nonlinear function to age cost [4] (refer to Table I). By incorporating such nonlinear function, nonlinear AoI seamlessly

TABLE I
THE COMPARISON OF DIFFERENT PERFORMANCE METRICS.

Metrics	Evolution Process Example	Mathematical Definition	Characteristics	Reflect $[C_{age}, C_{sync}, C_{async}]$
AoI		$\Delta_{\text{AoI}}(t) = t - U(t)$	The time duration from the generation of the latest successfully acknowledged message.	[1, 0, 0]
Nonlinear AoI		$\Delta_{\text{Nonlinear}}(t) = f(\Delta_{\text{AoI}}(t))$ $f(\Delta_{\text{AoI}}(t)) = e^{\Delta_{\text{AoI}}(t)}$	A nonlinear function of AoI, which describes the nonlinear age cost.	[1, 0, 0]
AoII		$\Delta_{\text{AoII}}(t) = f(t) \cdot g(X(t), \hat{X}(t))$ $f(t) = t - W(t)$ $g(X(t), \hat{X}(t)) = \begin{cases} 1, & X(t) \neq \hat{X}(t) \\ 0, & X(t) = \hat{X}(t) \end{cases}$	A (non)linear function of the time duration from the latest time slot that the received status is synchronized with real-time status.	[0, 0, 1]
UoI		$\Delta_{\text{UoI}}(t) = \mathbf{f}(t) \cdot g(X(t), \hat{X}(t))$ $\mathbf{f}(t) = \begin{cases} t - W(t), & \text{with prob. } 0.5 \\ e^{t - W(t)}, & \text{with prob. } 0.5 \end{cases}$ $g(X(t), \hat{X}(t)) = \begin{cases} 1, & X(t) \neq \hat{X}(t) \\ 0, & X(t) = \hat{X}(t) \end{cases}$	A nonlinear stochastic process of linear AoII, which describes the time-variant status estimation cost caused by environment.	[0, 0, 1]
SCoI		$\Delta_{\text{SoI}}(t) = f(t, g(X(t), \hat{X}(t)), \mathbf{p}(t))$ $f(t) = g(X(t), \hat{X}(t)) + \mathbf{p}(t)$ $g(X(t), \hat{X}(t)) = \lvert X(t) - \hat{X}(t) \rvert$ $\mathbf{p}(t) = p$	Constructed by actuation cost and status estimation cost to describe the age cost, synchronization cost, and asynchronization cost.	[1, 1, 1]

Notations and color representation:

AoI: Age of information
AoII: Age of incorrect information
UoI: Urgency of information
SCoI: Synchronization cost of information

$U(t)$: The generation time slot of the latest successfully acknowledged message.
$W(t)$: The latest time slot that the received status is synchronized with real-time status.
$X(t)$: The real-time status message.
$\hat{X}(t)$: The received/estimated status message.
$\mathbf{p}(t)$: The environment status, which affects the actuation cost at the terminal.
$[\mathbf{C}_{age}, \mathbf{C}_{sync}, \mathbf{C}_{async}]$: The age cost, synchronization cost, and asynchronization cost.

— 🟦 : Age cost — : Synchronization (zero) cost — 🟥 : Status estimation cost — 🟩 : Synchronizion (actuation) cost

adapts to a broader range of practical applications. Evidently, both AoI and nonlinear AoI are inherently *content-agnostic*, meaning they cannot reflect whether the received messages are correctly estimated (i.e., synchronized with real-time status messages from the physical world). Nevertheless, the practical reality often sees higher costs associated with asynchronized messages. This prompts the exploration of *content-aware* metrics, shedding light on the varying costs associated with correctly/wrongly estimated information.

Taking another stride in the pursuit of content-aware timeliness, AoII introduces a linear/nonlinear function quantifying the time duration since the latest time that the received message is synchronized with the real-time status message, termed as status estimation (or asynchronization) cost [5] (refer to Table I). Status estimation cost usually involves the potential energy waste and transmission overhead due to wrong status estimation. Considering time-variant nonlinear function, UoI reflects the time-variant cost owing to the variable external environment [6] via replacing the nonlinear function by a stochastic process related to external environment.

B. New Metric: Synchronization Cost of Information

The above performance metrics are all related to age/synchronization/asynchronization cost. However, these metrics only describe the message estimation performance (timeliness or accuracy) without considering the utilization or actuation based on estimated message, which is still way from effectiveness-oriented communication.

To capture the effectiveness of messages, we propose a new metric called SCoI, which moves a step forward toward both content-aware and task-aware effectiveness. Specifically, as demonstrated in Table I, a non-zero synchronization cost is introduced in SCoI, which implies the potential cost of actuation based on correctly estimated message and environment status. Also, status estimation cost is added to actuation cost when statuses between transceiver are asynchronized, because wrong estimation misleads the actuator to make biased actuation which decreases ultimate effectiveness.

The advantages of SCoI can be summarized as follows.

- Firstly, SCoI is a comprehensive metric which reflects both synchronization cost and asynchronization cost. Compared to existing content-aware metrics, SCoI is further effectiveness-aware by involving task actuation cost.

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- Secondly, SCoI is a unified metric which can reduce to the existing metrics. For instance, by setting the synchronization cost as zero, SCoI is then equivalent to AoII or UoI. Similarly, by setting actuation cost as age-aware, SCoI can reduce to (nonlinear) AoI.
- Thirdly, SCoI is also a generalized metric which can describe the effectiveness of most mission-critical applications in the SAGSIN. For instance, in error-sensitive services such as status monitoring, we choose cost functions whose values are proportional to status estimation error.

To better demonstrate how SCoI facilitates mission-critical applications in SAGSIN, we showcase a design method of SCoI for a specific application, namely remote fire rescuing.

Step 1: Exploring the task demands. Information timeliness and actuation preciseness are two basic demands, since timeliness ensures correct fire status estimation, while preciseness implies moderate (neither more nor less) rescue decision.

Step 2: Defining status estimation cost. A larger distance between estimated fire status and real-time original status causes more severe consequences. A function proportional to estimation error can be adopted here.

Step 3: Defining actuation cost. A moderate decision of rescue efforts just prevents fire from spreading while scheduling the least resources. We can use a function proportional to rescue resource consumption here.

Step 4: Designing SCoI. SCoI is equal to the status estimation cost plus actuation cost. Here, both synchronization cost and asynchronization cost are larger than zero because of effectiveness-oriented design.

IV. EFFECTIVENESS-ORIENTED SAGSIN BASED ON JPCCA FRAMEWORK

As mentioned in Section II, several characteristics of SAGSIN will pose a challenge of effectiveness degradation on the mission-critical applications. To overcome this challenge, a JPCCA framework integrating perception, communication, computing, and actuation techniques is introduced to sufficiently leverage and compensate the advantages of SAGSIN. In this section, we elaborate on how the four types of techniques are jointly designed for effectiveness-oriented SAGSIN based on JPCCA framework demonstrated in Figure 2.

A. Perception Techniques

Perception techniques compose the initial part of the JPCCA framework, for effective data perception and message generation will basically ensure the performance of communication and actuation techniques. Specifically, the multiple sensors, including thermometers, barometers, cameras, and remote sensing devices, etc, observe time-varying statuses/objects from the dynamic external environment. Because of the great diversity of sensors, two major issues exist in traditional perception technique design. Theoretically, in lossy compression, perceptual quality is determined by rate-distortion function, implying a trade-off between the three aspects. Practically, perception devices are usually limited in battery life, causing issue of limited energy resources for perception processes. To tackle these issues, a rate-distortion-perception trade-off theory can help guide the perception techniques [11]. Moreover, under the support of intelligent semantics compression techniques, the semantics of the multi-modal data can be extracted via AI-based semantics extractor which greatly compresses massive data [12].

B. Communication Techniques

Communication Techniques are the nucleus of the JPCCA framework, because effective routing, protocol and coding schemes guarantee accuracy and avoid collision of message transmission to further ensure ultimate effectiveness of system. Routing techniques aim at choosing the relay nodes to avoid communication conflicts; protocol design ensures reliable data exchange such as three-way handshake in transmission control protocol/Internet protocol (TCP/IP), ALOHA random access protocol, and chase combining in hybrid automatic repeat request (HARQ); coding schemes complete the mapping from message to modulated code words such that the latter contains as much information of the former as possible. To achieve highly effective communication with low collision and packet-loss probabilities while reducing bandwidth and power resources consumption, AI-based routing, protocol, and coding design should be adopted. For instance, in multi-user joint observation tasks, an AI-based medium access control policy can enhance the success rate of each user [13].

C. Computing Techniques

The mentioned perception, communication, and forthcoming actuation techniques are highly dependent on AI techniques, especially DL-based techniques like deep reinforcement learning (DRL) and deep federated learning (FL). Because of limited computing capabilities on terminal operators, computing techniques rely greatly on the edge/cloud servers distributed in SAGSIN, such as maritime base stations, LEO/GEO satellites, and ground base stations. Integrating the computing devices/resources (e.g., CPUs, graphics processing units (GPUs), memories, and caching spaces) deployed on edge, cloud, and terminal operators, the cloud-edge-end network provides sufficient resources for computation offloading. Small-scale computing tasks can be offloaded to nearby edge servers with ample computing resources, and large-scale ones are further offloaded to remote cloud servers with substantial resources. This implies a trade-off between edge-end (or cloud-end) transmission latency and computing resources. For instance, in fog computing (an extension of cloud computing which is similar to edge computing) scenario, an intelligent and dynamic computation offloading algorithm can achieve lower overall latency while saving energy consumption [14].

D. Actuation Techniques

Actuation techniques are a vital part of the JPCCA because of affecting the ultimate effectiveness of the mission-critical applications. Effective actuation command will guide the terminal operators to conduct precise behavior to pose positive impact on environment statuses of the network and

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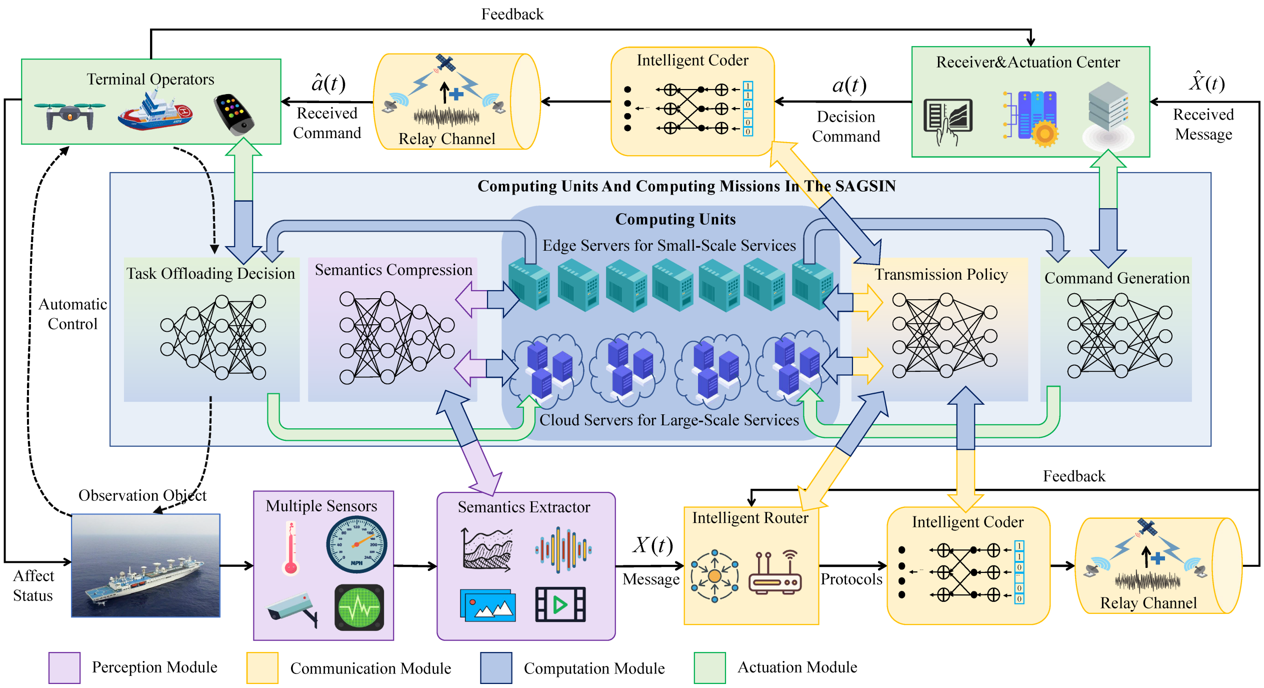

Fig. 2. The framework of joint perception-communication-computing-actuation.

thus yield ultimate effectiveness. Specifically, an intelligent actuator completes the estimation on received messages and decides what commands are generated according to the estimation performance (e.g. cost caused by actuation error) of received messages [15]. After command generation, the commands are also transmitted utilizing intelligent communication techniques. As the command estimation and corresponding task execution are conducted by the terminal operators, the environment statuses are positively affected (e.g. the timely rescue on sinking ships), and a perception-communication-actuation closed loop is thus established.

E. JPCCA Design Details

In the AI-aided mission-critical application based on the JPCCA framework, the physical process unfolds as illustrated in Figure 2. Firstly, multiple sensors observe both the object and the environment, sampling and generating moderate status messages through a semantic extractor. Secondly, an intelligent transmitter employs a tailored transmission scheme, adapting to the environmental conditions and the semantic content of the messages. Thirdly, the messages are received by remote actuation center, where decision commands are computed based on the current message semantics and the knowledge acquired from previous statuses and actuation. Fourthly, after command transmission, terminal operators execute these commands, potentially affecting the status of the network.

To jointly optimize the effectiveness performance of such closed-loop framework, decentralized sequential decision optimization techniques can be adopted. The reason why decentralized policies are chosen is that JPCCA framework involves nodes which are sparsely distributed and far from each other in SAGSIN. Specifically, each node that performs one of perception, communication, or actuation processes can be treated as an intelligent agent. Due to limited capabilities of nodes, agents can observe only a small portion of the whole state information from the external environment (i.e., the statuses of mission-critical applications), and calculate a decision based on the observed partial state. By observations and decisions, these agents interact with external environment and learn to decide actions more effectively.

Evidently, agents cannot acquire global observation on the environment, while they will affect each other via decision processes since they share the same goal. Therefore, optimizing each agent independently is not globally optimal. Instead, a multi-agent Markov decision process (MDP) optimization can facilitate each agent in choosing the best decisions under various states. We consider a mission-critical application with task offloading, where perception, communication, and actuation techniques should be partly conducted at edge/cloud servers. Each agent should decide whether offloading its computation task to near servers or conducting by itself, while the communication bandwidth and computing speed are limited. Because the agents all aim at effectively conducting identical mission, constrained MDP optimization with agents sharing reward function can solve such problem by jointly allocating communication/computing resources.

V. CASE STUDY

A. UAV-based Multi-object Detection & Tracking

In this subsection, we showcase how the proposed SCoI and JPCCA framework enhance the effectiveness of mission-critical applications through study on UAV-based multi-object detection & tracking tasks. As illustrated in Figure 3, several UAVs continuously detect and track abnormal mobile objects

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(e.g., illegal ships or emergencies) in a sea area. Moreover, several HAPs with global perception capabilities observe the whole sea area, capture the positions of UAVs and objects, and transmit the captured information to UAVs. UAVs then decide their own flight actions to maintain tracking on objects. We call the event as successful task actuation, if all the objects are successfully tracked and moderately dealt with (e.g., being driven away or rescued). The techniques of dealing with objects are beyond the scope of this article.

As a case study, we simplify the system model and give initial numerical results. Specifically, only one HAP provides global perception and only one UAV tracks several objects one-by-one. Considering limited device capabilities and highly dynamic task environment, HAP and UAV should work cooperatively to effectively complete tasks while saving energy. HAP should refine its perception & communication policies to maximize the timeliness/effectiveness of information (e.g., AoI/SCoI), while UAV adopts adaptive actuation policy to maximize the effectiveness of flight actions (e.g., minimize UAV-object distances). Thus, HAP and UAV can be treated as intelligent agents, and computing techniques like multi-agent DRL can solve the MDP problem. Within each time step, HAP agent decides whether to transmit the currently perceived UAV/object coordinates based on uplink channel SNR and timeliness/effectiveness of information, while UAV agent decides its flight direction and speed based on its estimation (originated from HAP transmission) of object coordinates. By joint training using timeliness/effectiveness of information as reward function, timeliness/effectiveness-oriented JPCCA frameworks are respectively constructed.

To represent the effectiveness of tracking task, we define SCoI as the distance between real-time status and estimated status multiplied by the number of existing objects, plus the battery cost of UAV flight. This definition can reflect the status estimation cost, task process, and actuation cost. To demonstrate the superiority of the proposed metric and framework, we also choose two baseline policies, namely uniform transmission and change-aware transmission. Using the same actuation policy as AoI/SCoI-optimal JPCCA framework, HAP transmits perceived information every two steps under the former policy, while transmits when objects move (i.e., information changes) under the latter policy.

B. Numerical Results

To evaluate the QoS of object tracking tasks under each policy, we compare the average SCoI per step, average reward per step (SCoI plus battery cost of HAP transmission), and average total time steps of once successful task actuation. SCoI and reward function indirectly, while the time duration of task actuation directly, reflects the ultimate effectiveness-oriented QoS of the task.

Figure 4 illustrates the average SCoI and reward under different policies, and for the same policy, the distance between reward curve and SCoI curve represents transmission energy cost, also the transmission frequency. Compared to other baselines, SCoI-optimal policy achieves the highest effectiveness (lowest SCoI) while transmitting less information, because more valuable statuses are selected with less important ones discarded. That is, under SCoI-optimal policy, limited communication resources are moderately allocated for information which is most useful for UAV to successfully complete the task.

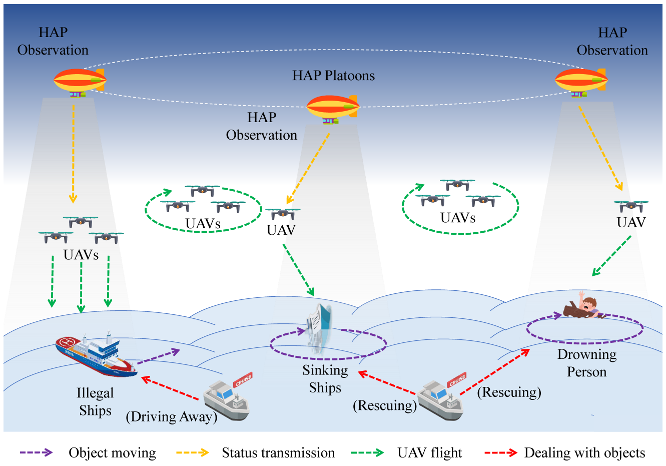

Fig. 3. An illustration of UAV-based object detection & tracking task in SAGSIN.

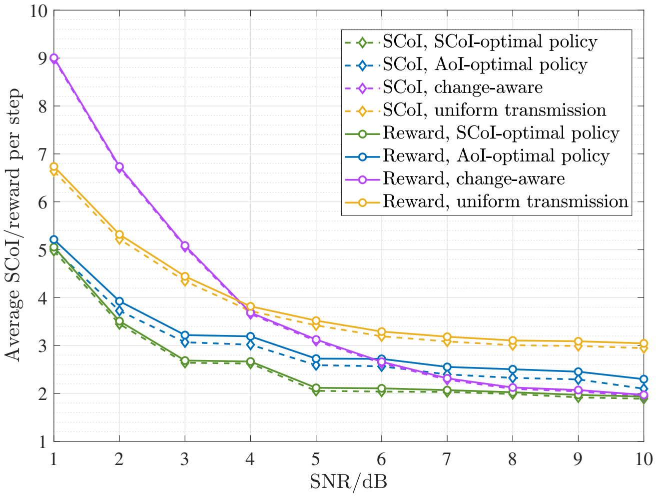

Fig. 4. The average SCoI and reward of SCoI-optimal, AoI-optimal, and baseline policies.

We further illustrate the average time for successful task actuation under different policies in Figure 5, with red numbers in bars representing average transmission frequency. Under SCoI-optimal policy, a better trade-off between task execution performance and energy cost is struck considering limited battery of HAP. Compared to AoI-optimal policy where statuses are transmitted at almost every time slot, SCoI-optimal policy achieves similar effectiveness performance while saving more than half battery, which better satisfies the demand of mission-critical applications in SAGSIN.

VI. OPEN ISSUES

To pave the way for effectiveness-oriented SAGSIN implementation in the future 6G networks, some open issues are

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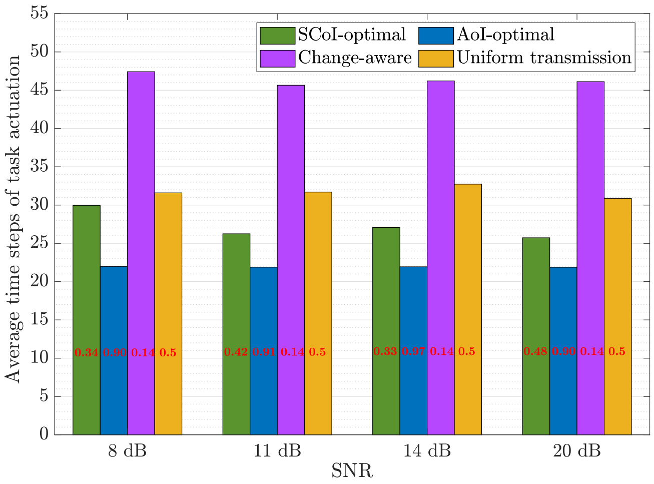

Fig. 5. The average task actuation time of SCoI-optimal, AoI-optimal, and baseline policies.

still to be solved, including but not limited to the following research areas.

More concrete effectiveness metrics: In this article, we propose a new metric called SCoI, which can unify existing metrics. In fact, in more general applications, the effectiveness metrics related to costs can be further refined. For instance, costs can vary according to which status is wrongly estimated; costs can be dependent on environment variation; also, costs can be related to time duration. These call for a comprehensive multi-dimensional effectiveness metric which describes the above aspects for mission-critical applications in SAGSIN.

Joint sampling-routing-protocol-coding communication techniques: As mentioned in Section IV, AI-based adaptive sampling, routing, protocol, and coding play significant roles in the JPCCA framework. However, effectiveness-oriented joint sampling-routing-protocol-coding scheme is still in its infant age. The co-design scheme will further lighten the burden of the network by integrating these techniques and using only one intelligent module for realization, which implies a lite AI-based JPCCA framework for future SAGSIN.

Resource management in SAGSIN: The SAGSIN is a heterogeneous network which sufficiently leverage the advantages of each component to achieve high effectiveness. Nevertheless, all-inclusive networks inevitably pose challenges when considering resource management, since utilizing a certain component of SAGSIN to increase effectiveness produces its corresponding cost, which may conversely decrease effectiveness. For example, in cloud-edge-end computing, if we pursue high effectiveness by leveraging computing resources on remote edge/cloud servers instead of terminal operators, the long propagation delay will counteract. Therefore, proper management on available resources is imperative to avoid harm to effectiveness.

VII. CONCLUSION

In this article, we have proposed a comprehensive performance metric called SCoI to measure the effectiveness of mission-critical applications in the SAGSIN, and proposed the JPCCA framework to enhance the effectiveness. By introducing cloud-edge-end computing techniques, we have designed an intelligent effectiveness-oriented closed-loop remote communication system in SAGSIN, supported by multi-modal data perception, adaptive communication, and effectiveness-oriented actuation techniques. Simulation of UAV-based object tracking case demonstrates the superiority of proposed JPCCA framework in terms of effectiveness.

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