

Article

Age-Aware Collaborative Scheduling for Ensuring Data Freshness in WBAN-Based Health Monitoring Systems

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Abstract

Wireless body area networks (WBANs) for healthcare monitoring require age-of-information (AoI)-aware resource allocation under heterogeneous periodic and aperiodic traffic. Existing AoI-aware resource allocation methods can be broadly divided into centralized, decentralized, and hybrid approaches, but each has a structural limitation: centralized scheduling may allocate time slots to sources without newly generated samples, decentralized access may suffer from collision-induced delay under heavy contention, and fixed hybrid access may fail to adapt the scheduled and random access regions to the current traffic composition. To jointly address these limitations, this paper formulates a sample-wise weighted AoI minimization problem that accounts for source-specific sampling periods, transmission lengths, and priority weights, and proposes an online collaborative hybrid scheduler. The proposed method extracts traffic features at runtime, classifies sources as periodic or aperiodic, schedules periodic samples through contention-free access close to their sampling start times, and supports aperiodic samples through random access without pre-reserving slots. It further adapts the contention-free and random access regions according to the detected traffic composition. Simulation results show that the proposed scheduler reduces sample-wise weighted AoI compared with centralized and decentralized AoI schedulers by mitigating incorrect scheduling, reducing collision-induced delay, and improving superframe utilization.

Keywords: age of information; age-aware scheduling; heterogeneous traffic flow; centralized scheduling; decentralized scheduling

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1. Introduction

Wireless body area networks (WBANs) have become an essential communication paradigm for continuous and unobtrusive healthcare monitoring, where multiple wearable or implantable sensor nodes collect physiological signals and transmit them to a coordinator or a fusion center. Typical WBAN applications include electrocardiogram (ECG), electroencephalogram (EEG), blood pressure, body temperature, glucose, and motion monitoring. In such applications, the value of the received information depends not only on whether packets are successfully delivered but also on how fresh the delivered information is. Therefore, age of information (AoI), which measures the elapsed time since the generation time of the latest successfully received update, has been widely adopted as a key metric for time-sensitive monitoring and control systems [1,2].

In WBAN-based healthcare monitoring systems, minimizing the system-wide average AoI is particularly important because stale physiological information may degrade monitoring accuracy and delay subsequent medical or control decisions. Compared with conventional metrics such as throughput, latency, and packet delivery ratio, AoI jointly captures the effects of sampling, queuing, scheduling, transmission failure, and retransmission. Hence, an AoI-aware WBAN scheduler should determine not only which node should transmit but also whether a newly generated update actually exists at the scheduled node. This issue becomes more challenging in practical WBANs because sensor nodes have heterogeneous sampling periods, required transmission lengths, priorities, and traffic regularities [3].

1.1. Background

Existing AoI-oriented resource allocation methods can be broadly categorized into centralized, decentralized, and hybrid approaches. Centralized approaches assume that a coordinator, base station, or controller determines the transmission schedule of multiple sources. Such approaches have been extensively studied for AoI minimization under unreliable channels, stochastic arrivals, throughput constraints, interference constraints, and learning-based resource allocation [4–13]. These studies provide important mathematical foundations for AoI-aware scheduling. However, many centralized AoI schedulers are built on simplified traffic assumptions, such as full-buffer sources, synchronized update availability, homogeneous packet lengths, or abstract wireless links. In a WBAN with heterogeneous sampling periods, such assumptions may lead to an incorrect scheduling problem. Specifically, if a coordinator allocates a time slot to a source only because its AoI is large, the source may still have no newly generated data at that time. The allocated slot is then wasted, while other sources with available updates remain unserved. This mismatch between AoI-based priority and actual data availability can increase the waiting time of fresh updates and raise the system average AoI.

Decentralized approaches address a different aspect of the problem. Instead of relying on a global coordinator to preallocate every transmission opportunity, each source independently contends for channel access when it has an update to transmit. Random access mechanisms such as slotted ALOHA, age-threshold ALOHA, carrier sense multiple access (CSMA), frame slotted ALOHA, grant-free access, and non-orthogonal multiple access (NOMA)-assisted random access have been studied from the AoI perspective [14–24]. These methods are attractive for unpredictable or sporadic traffic because a node without data does not participate in contention, thereby naturally avoiding the incorrect scheduling problem. However, when many sources generate updates frequently, decentralized contention can cause frequent collisions, backoff delays, and retransmissions. Since AoI increases while a generated update waits for successful delivery, collision-induced delay can significantly increase the average AoI, especially for high-priority or short-sampling-period sources.

Hybrid approaches attempt to combine scheduled and contention-based access. In WBANs, this idea is also consistent with the IEEE 802.15.6 superframe structure [25], where managed access phases and random access phases can coexist. From an AoI perspective, hybrid access is promising because periodic traffic can be handled by scheduled transmissions, whereas aperiodic traffic can be handled by random access. Recent studies on scheduled versus random access, hybrid automatic repeat request (HARQ)/automatic repeat request (ARQ)-based status updating, grant-free access, and semi-grant-free transmission also suggest that different access modes have different AoI trade-offs depending on traffic load, channel reliability, feedback, and resource availability [22,26–30]. Nevertheless, a fixed hybrid structure may still be inefficient if the lengths or positions of scheduled and

random access periods are not adapted to the actual traffic composition. If the contention-free part is too long, slots may be wasted by nodes without newly generated data. If the random access part is too long, collisions and backoff overhead may dominate. Therefore, a hybrid scheduler for WBANs should be adaptive rather than static.

1.2. Our Contributions

Motivated by these observations, this paper investigates the weighted average AoI minimization problem in WBAN-based healthcare monitoring systems with heterogeneous traffic. The unresolved gap in the literature is that existing centralized, decentralized, and hybrid AoI schedulers do not jointly address the following three coupled issues: (i) incorrect scheduling caused by the mismatch between AoI-based priority and actual data availability, (ii) collision- and retransmission-induced AoI growth in decentralized access, and (iii) non-adaptive superframe partitioning under mixed periodic and aperiodic traffic. This gap is particularly critical in WBANs because sensor nodes may have highly different sampling periods, packet lengths, priorities, and traffic regularities.

The key idea of this work is to interpret WBAN AoI minimization as an online collaborative hybrid scheduling problem. The proposed method is online because the coordinator does not assume complete prior knowledge of all traffic patterns; instead, it estimates traffic features at runtime. It is collaborative because centralized slot allocation and decentralized random access are jointly used. It is hybrid because periodic and aperiodic traffic are handled by different but coordinated access mechanisms. Unlike prior AoI-aware hybrid scheduling methods that mainly combine scheduled and random access in a fixed or access-probability-based manner, the proposed method explicitly links the access-mode decision to the estimated sampling period, required transmission length, priority weight, and traffic regularity of each source.

From a mathematical viewpoint, the original problem is a combinatorial optimization problem. The scheduler must determine how to assign finite transmission opportunities under heterogeneous sampling intervals, packet lengths, priority weights, and traffic types. Exhaustively searching all feasible arrangements is computationally prohibitive as the number of sources and the superframe length increase. Therefore, this work focuses on an online optimization-oriented scheduling perspective that can support practical WBAN operation while addressing the structural limitations of centralized, decentralized, and fixed hybrid approaches.

The main contributions of this work are summarized as follows:

- We identify the incorrect scheduling problem in heterogeneous WBAN-based healthcare monitoring systems, where conventional AoI-aware schedulers may allocate transmission slots to sources without newly generated updates, thereby wasting resources and increasing the weighted average AoI.
- We formulate the weighted average AoI minimization problem by incorporating source-specific sampling periods, required transmission lengths, and priority weights. This formulation highlights the need for traffic-aware scheduling beyond conventional age-based priority decisions.
- We propose an online collaborative scheduling framework that integrates centralized scheduling for periodic sources and decentralized random access for aperiodic sources. This framework jointly addresses the limitations of purely centralized, purely decentralized, and fixed hybrid access mechanisms.
- We develop runtime traffic feature extraction and age-aware slot allocation mechanisms that estimate each source's traffic characteristics and align scheduled transmissions with the sampling start times of periodic sources, thereby reducing empty-buffer scheduling and improving resource utilization.

- We design a dynamic superframe adaptation method that inserts random access periods for aperiodic sources while limiting the disruption to scheduled periodic traffic, and we validate the proposed method against representative centralized and decentralized AoI schedulers under heterogeneous WBAN traffic conditions.

2. Related Work

2.1. Centralized AoI Scheduling

Centralized AoI scheduling has been widely investigated as a mathematical optimization problem in which a coordinator, base station, or central controller determines the transmission schedule of multiple sources. Early AoI studies established the basic relationship between update generation, service process, and information freshness [1,2]. Building on this foundation, centralized wireless scheduling policies were developed to minimize average AoI under unreliable channels, stochastic arrivals, throughput constraints, and interference constraints [4–9].

Recent studies have further extended centralized AoI optimization to more complex and practical settings. Li et al. [10] proposed a deep-reinforcement-learning-based resource scheduling method for industrial Internet of Things (IoT) systems. Liu and Chen [11] considered a pull-based multiuser wireless uplink system and optimized the AoI at query using a Whittle-index approach. Lin et al. [12] studied information-age aware task scheduling (IATS) in vehicle-road-cloud cooperative systems. Wang et al. [13] proposed a world-model-based learning framework for long-term AoI minimization in vehicular networks. These recent studies show that AoI minimization is increasingly formulated as a structured decision-making problem involving scheduling, resource allocation, task placement, and long-term system dynamics.

However, most centralized AoI schedulers assume that update availability is either known, statistically modeled, or abstracted in a way that does not fully capture WBAN traffic heterogeneity. In practical WBANs, a source with a large AoI may not have newly generated data if its sampling period is long. Scheduling such a source wastes the allocated slot and delays other sources with available updates. Therefore, centralized scheduling alone may suffer from the incorrect scheduling problem when applied to heterogeneous WBAN traffic.

2.2. Decentralized AoI Scheduling

Decentralized AoI scheduling has been studied mainly through random access mechanisms. In these approaches, each source decides whether to transmit based on local information such as its AoI, update availability, channel state, or access probability. Slotted ALOHA, age-threshold ALOHA, CSMA, frame slotted ALOHA, and grant-free access have been analyzed from the AoI perspective [14–17]. These approaches are well suited for systems in which traffic arrivals are unpredictable or difficult to estimate because a source can contend for access immediately after generating a new update.

More recently, Moradian et al. [18] proposed an AoI-aware dynamic frame slotted ALOHA protocol in which the frame length and age-gain threshold are adjusted to improve the average AoI reduction. Zhao et al. [19] optimized information freshness in mobile networks using age-threshold slotted ALOHA. Zhao et al. [20] studied AoI in energy-harvesting random access networks with finite-blocklength transmissions. Ding et al. [21] analyzed the impact of NOMA on AoI from a grant-free transmission perspective. Sun et al. [22] analyzed NOMA-assisted grant-free transmissions with randomly arrived packets and evaluated the effect of retransmission on the average AoI. Li et al. [24] investigated channel probing and reservation for improving AoI in energy-harvesting random access networks. These recent studies demonstrate that decentralized

AoI minimization is strongly affected by access probability, collision, retransmission, energy availability, and update generation randomness.

Despite their flexibility, decentralized schemes are vulnerable to contention overhead. When many sources have fresh updates at the same time, collisions and backoff procedures increase the time required for successful delivery. This is critical for AoI minimization because AoI continues to grow while updates wait for channel access. In WBANs with short-sampling-period or high-priority sources, repeated contention can therefore offset the benefit of immediate access. This motivates a scheduler that does not allow all sources to contend blindly, but instead restricts random access to the traffic types for which scheduled allocation is inefficient.

2.3. Hybrid and Adaptive Access for AoI Minimization

Hybrid access combines scheduled and random access mechanisms. In the context of WBANs, such a structure is naturally related to the IEEE 802.15.6 superframe, where managed access and random access phases can coexist [25]. From an AoI minimization perspective, this is attractive because periodic traffic can be scheduled in a contention-free manner, while sporadic traffic can access the channel through random access.

Recent studies also support the importance of selecting an appropriate access mode according to traffic and network conditions. Yue et al. [28] directly compared random access and scheduled access from the perspective of timeliness. Their results support the observation that neither access mode is universally optimal; rather, the preferred access mechanism depends on traffic load, contention intensity, and scheduling overhead. In addition, recent grant-free and NOMA-based studies [21–23] show that immediate access can improve freshness but may also introduce collision, decoding, and retransmission-related trade-offs. HARQ- and ARQ-related AoI studies further indicate that retransmission delay must be considered when evaluating freshness in unreliable wireless systems [26,27]. Channel modeling and estimation studies, including quantized deep learning-based channel estimation for RIS-gMIMO systems [31], also motivate the need to clarify propagation loss, channel uncertainty, and interference assumptions when evaluating wireless freshness.

However, existing hybrid access studies do not directly solve the WBAN-specific incorrect scheduling problem under heterogeneous sampling periods. A fixed division between scheduled and random access periods may waste resources when the ratio of periodic and aperiodic sources changes. Therefore, the key issue is not simply whether a system uses both access modes, but whether it adapts the scheduled and random access regions according to online traffic characteristics.

2.4. Summary of Literature and Research Gap

Table 1 summarizes the inferences from the literature survey. The table highlights that centralized, decentralized, and hybrid AoI schedulers each address only part of the problem. Centralized scheduling provides controllable slot allocation but can suffer from incorrect scheduling under heterogeneous sampling. Decentralized scheduling avoids scheduling inactive nodes but suffers from collision and backoff delay. Hybrid scheduling combines both access modes but often lacks online adaptation of the scheduled and random access regions. This paper addresses this gap by considering source-specific sampling periods, required slots, priority weights, and traffic regularity in a unified online collaborative scheduling structure.

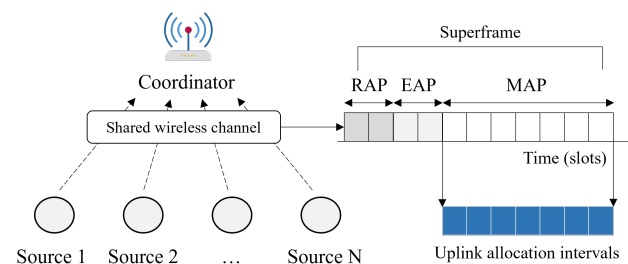
Table 1. Summary of literature survey and unresolved gaps.

Category	Representative Studies and Key Idea	Limitation for Heterogeneous WBAN Traffic	Gap Addressed by This Paper
Centralized AoI scheduling	Centralized schedulers optimize AoI or AoI-related cost through coordinator-controlled scheduling [4–13].	They may allocate slots to sources without newly generated data when traffic is heterogeneous or non-full-buffer.	The proposed method uses traffic-aware scheduling for periodic sources to reduce incorrect scheduling.
Decentralized AoI scheduling	Random access schemes allow sources to contend based on local age, threshold, probability, or grant-free access [14–24].	Collision, backoff, and retransmission delay can increase rapidly under high traffic load.	Random access is mainly assigned to aperiodic sources to limit unnecessary contention.
Hybrid/adaptive access	Hybrid schemes combine scheduled and random access to support different traffic types [21,22,25–30].	Fixed or insufficiently adaptive scheduled/random access partitioning may waste resources.	The proposed method adapts scheduled and random access regions according to traffic regularity.

3. System Model and Problem Statement

3.1. Target System

As illustrated in Figure 1, we consider a wireless body area network (WBAN)-based healthcare monitoring system composed of one coordinator and a set of heterogeneous body sensor nodes. Let $\mathcal{N} = \{1, 2, \dots, N\}$ denote the set of source nodes. The body sensors are connected to the coordinator through a one-hop star topology. Each source node monitors a physiological signal and generates data samples according to its own traffic pattern. The coordinator manages uplink resource allocation and receives sampled data from the source nodes.

**Figure 1.** Illustration of the considered WBAN-based healthcare monitoring system.

The system follows the IEEE 802.15.6 beacon-enabled superframe structure. A superframe provides both scheduled and contention-based access opportunities. In this paper, the scheduled access region is referred to as the contention-free period (CFP), where the coordinator explicitly allocates transmission slots to selected sources. The contention-based access region is referred to as the random access period (RAP), where sources contend for transmission opportunities when they have data to send. The exclusive access phase (EAP) can be interpreted as a priority-aware random access region for high-priority traffic, whereas the managed access phase (MAP) supports scheduled uplink transmissions. For clarity, the terms CFP and RAP are used to distinguish scheduled and random access resources, respectively.

Each source node i is characterized by

$$(P_i, L_i, W_i), \quad (1)$$

where P_i is the sampling period, L_i is the number of time slots required to transmit one sample, and W_i is the priority weight. A larger W_i indicates a more critical physiological data source. The coordinator does not assume that these parameters are perfectly known in advance. Instead, it estimates the traffic features of each source at runtime and classifies each source as either periodic or aperiodic. Let $\mathcal{P}$ and $\mathcal{A}$ denote the sets of periodic and aperiodic sources, respectively, where

$$\mathcal{P} \cup \mathcal{A} = \mathcal{N}, \quad \mathcal{P} \cap \mathcal{A} = \emptyset. \quad (2)$$

For a periodic source $i \in \mathcal{P}$, the k -th sample is generated at

$$g_{i,k} = s_i + (k-1)P_i, \quad (3)$$

where s_i is the initial sampling start time. For an aperiodic source $i \in \mathcal{A}$, the generation time $g_{i,k}$ is not known in advance. This distinction is central to the proposed scheduling design: periodic samples can be scheduled according to their estimated sampling pattern, whereas aperiodic samples should not be assigned reserved CFP slots before their actual generation.

3.2. Sample-Wise Weighted AoI Minimization

Conventional AoI models often define one age process for each source node. However, in heterogeneous WBAN traffic, the freshness of each generated physiological sample should be explicitly considered because different samples from the same source may experience different waiting times, transmission opportunities, or losses. Therefore, we define the sample-wise AoI of the k -th sample generated by source i as

$$A_{i,k}^s(t) = t - g_{i,k}, \quad t \geq g_{i,k}, \quad (4)$$

where $g_{i,k}$ denotes the generation time of sample k from source i . Since $g_{i,k}$ is fixed after sample generation, $A_{i,k}^s(t)$ increases linearly with slope one while the sample remains pending.

The objective of the scheduler is to minimize the long-term sample-wise weighted average AoI, defined as

$$\bar{A}^s = \lim_{T \rightarrow \infty} \frac{1}{T \sum_{i \in \mathcal{N}} |\mathcal{K}_i(T)|} \sum_{t=1}^T \sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{K}_i(T)} W_i A_{i,k}^s(t), \quad (5)$$

where $\mathcal{K}_i(T)$ is the set of samples generated by source i during the time horizon T . This formulation extends the conventional node-level weighted AoI objective to a sample-wise form by evaluating the freshness cost of each generated sample.

To formally express the scheduling problem, consider a superframe with M uplink slots, denoted by $\mathcal{M} = \{1, 2, \dots, M\}$. We define the following decision variables:

- $x_{i,k,t} \in \{0, 1\}$: equals 1 if sample k of source i starts its scheduled CFP transmission at slot t ; otherwise, 0.
- $r_t \in \{0, 1\}$: equals 1 if slot t is assigned to the RAP; otherwise, 0.
- $y_{i,k} \in \{0, 1\}$: equals 1 if sample k of source i is successfully transmitted; otherwise, 0.

The sample-wise weighted AoI minimization problem is formulated as

$$\mathbf{P1} : \min_{\{x_{i,k,t}\}, \{r_t\}, \{y_{i,k}\}} \bar{A}^s \quad (6)$$

$$\text{s.t. } x_{i,k,t}, r_t, y_{i,k} \in \{0, 1\}, \quad (7)$$

$$\sum_{i \in \mathcal{P}} \sum_k \sum_{\tau: t \in \{\tau, \tau+1, \dots, \tau+L_i-1\}} x_{i,k,\tau} + r_t \leq 1, \quad \forall t \in \mathcal{M}, \quad (8)$$

$$x_{i,k,t} = 0, \quad \forall i \in \mathcal{P}, \forall k, \forall t < g_{i,k}, \quad (9)$$

$$\sum_{t=g_{i,k}}^{g_{i,k+1}-1} x_{i,k,t} \leq 1, \quad \forall i \in \mathcal{P}, \forall k, \quad (10)$$

$$x_{i,k,t} = 0, \quad \forall i \in \mathcal{A}, \forall k, \forall t, \quad (11)$$

$$\sum_{t \in \mathcal{M}} r_t \geq R_{\min}. \quad (12)$$

Constraint (8) ensures that each time slot is used either by one scheduled CFP transmission or by RAP, but not both. Constraint (9) prevents a periodic sample from being

scheduled before it is generated. Constraint (10) allows at most one scheduled transmission opportunity for each periodic sample within its sampling interval. Constraint (11) states that aperiodic samples are not assigned pre-reserved CFP slots because their generation times are not known in advance. Constraint (12) guarantees a minimum amount of RAP resources for aperiodic traffic.

Problem **P1** is a combinatorial optimization problem because the coordinator must jointly determine scheduled CFP slot placement and RAP allocation under heterogeneous P_i , L_i , and W_i . Since exhaustive search over all feasible CFP/RAP configurations is computationally prohibitive, this paper develops an online collaborative scheduling approach to approximate the solution of **P1**.

3.3. Notation Summary

For clarity, Table 2 summarizes the main notation used in the system model, optimization formulation, and proposed algorithms.

Table 2. Summary of main notation.

Notation	Description
$\mathcal{N}$	Set of source nodes
N	Number of source nodes
$\mathcal{P}$	Set of periodic sources
$\mathcal{A}$	Set of aperiodic sources
i	Source index
k	Sample index
t	Time-slot index
P_i	Sampling period of source i
L_i	Number of slots required to transmit one sample of source i
W_i	Priority weight of source i
$u_{i,k}$	k -th sample generated by source i
$g_{i,k}$	Generation time of sample $u_{i,k}$
$A_{i,k}^s(t)$	Sample-wise AoI of sample $u_{i,k}$ at time t
$\bar{A}^s$	Long-term sample-wise weighted AoI
$\mathcal{M}$	Set of uplink slots in a superframe
M	Number of uplink slots in a superframe
$x_{i,k,t}$	Binary CFP scheduling variable for sample $u_{i,k}$ at slot t
r_t	Binary RAP assignment variable for slot t
$y_{i,k}$	Binary successful transmission indicator for sample $u_{i,k}$
$R_{\min}$	Minimum number of RAP slots required in a superframe
V	Uplink allocation vector
$V_{\max}$	Maximum length of the uplink allocation vector
U_i	Preemption utility of source i
γ_{gain}	Priority-weighted gain caused by preemption
γ_{loss}	Priority-weighted loss caused by preemption or RAP insertion
BO_i	Backoff counter of source i
$BO_{\max}$	Maximum allowable backoff or retransmission attempts

3.4. Computational Hardness and Online Approximation

The finite-horizon version of problem **P1** is computationally hard because the coordinator must place multiple samples with heterogeneous transmission lengths into a finite superframe while satisfying slot exclusivity, causality, and CFP/RAP partitioning constraints. This structure is closely related to classical single-machine scheduling problems.

Theorem 1. *The finite-horizon sample-wise weighted AoI minimization problem is NP-hard.*

Proof. We prove the claim by showing that a known NP-hard scheduling problem is a special case of **P1**. Consider the single-machine weighted tardiness minimization problem, denoted by $1||\sum_j w_j T_j$, where each job j has processing time p_j , weight w_j , due date d_j , completion time C_j , and tardiness $T_j = \max\{0, C_j - d_j\}$. The objective is to find a non-overlapping schedule that minimizes $\sum_j w_j T_j$. This problem is known to be NP-hard.

We construct a restricted instance of **P1** as follows. Let each job j correspond to one generated sample $u_{i,k}$. Set the required transmission length of the sample to the processing time of the job, i.e., $L_i = p_j$, and set the priority weight of the source to the job weight, i.e., $W_i = w_j$. The superframe slots correspond to the time positions of the single machine, and the slot exclusivity constraint in **P1** enforces the same non-overlap condition as the single-machine scheduling constraint. We further consider only periodic samples and disable RAP allocation by setting $R_{\min} = 0$, so that the problem reduces to arranging scheduled CFP transmissions only.

To represent the due-date-related freshness requirement, define a maximum desirable delivery time $d_{i,k}$ for sample $u_{i,k}$ and assign an additional age penalty when the completion time exceeds $d_{i,k}$. Then the delayed freshness cost of sample $u_{i,k}$ is proportional to

$$W_i \max\{0, c_{i,k} - d_{i,k}\},$$

which is equivalent to the weighted tardiness term $w_j T_j$ under the above mapping. Therefore, any algorithm that solves this restricted version of **P1** can solve the corresponding instance of $1||\sum_j w_j T_j$.

Since $1||\sum_j w_j T_j$ is NP-hard and it is a special case of the finite-horizon sample-wise weighted AoI minimization problem, **P1** is also NP-hard. $\square$

This result does not imply that the proposed algorithm finds a globally optimal offline solution. Rather, the proposed method is designed as an online approximation framework. The offline optimum would require complete knowledge of future sample generation times and an exhaustive search over feasible CFP/RAP configurations. Such information is unavailable in practical WBAN operation. Therefore, the proposed scheduler uses runtime traffic estimation and decomposes the original combinatorial problem into tractable online decisions: CFP scheduling for periodic samples, RAP access for aperiodic samples, and online superframe adaptation. The resulting schedule is not globally optimal in the offline sense, but it provides a polynomial-time online approximation structure that directly targets the dominant causes of AoI increase, namely incorrect scheduling and contention-induced delay.

3.5. Technical Challenges

The formulation above shows that minimizing sample-wise weighted AoI is not equivalent to simply selecting the source with the largest current age. The scheduler must jointly consider sample generation, data availability, transmission length, priority, traffic regularity, and access mode. This leads to three technical challenges.

3.5.1. Limitation of Centralized Scheduling

In centralized scheduling, the coordinator determines transmission opportunities for all sources. This approach is effective when traffic is periodic, predictable, and continuously available. However, many centralized AoI schedulers implicitly rely on a full-buffer or always-available update model. Under heterogeneous WBAN traffic, this assumption can cause incorrect scheduling.

The incorrect scheduling problem occurs when a source is allocated a CFP slot although no newly generated sample is available in its buffer. The slot is then wasted, and other pending samples remain undelivered. This is particularly harmful in sample-wise AoI minimization because the freshness penalty is accumulated for individual samples. If high-priority or frequently sampled sources are delayed due to slots wasted by inactive sources, the weighted AoI can increase rapidly.

Therefore, centralized scheduling is suitable for periodic sources only when their sampling periods are known or accurately estimated. This motivates a traffic-aware CFP design in which scheduled slots are aligned with the sampling start times of periodic sources.

3.5.2. Limitation of Decentralized Scheduling

In decentralized scheduling, sources contend for the channel after generating samples. This avoids incorrect scheduling because a source without a sample does not participate in contention. Therefore, decentralized random access is attractive for aperiodic or event-driven traffic.

However, decentralized access suffers from collision, backoff, and retransmission overhead when many sources contend simultaneously. In WBANs with high-priority or short-sampling-period sources, frequent contention can delay successful delivery and increase sample-wise AoI. Moreover, if all sources, including predictable periodic sources, are allowed to contend in the RAP, then the RAP can become overloaded even though periodic sources could be served more efficiently through CFP scheduling.

Therefore, decentralized access should not be applied uniformly to all sources. It is more appropriate to reserve RAP resources mainly for aperiodic sources whose generation times are difficult to predict.

3.5.3. Limitation of Fixed Hybrid Scheduling

Hybrid scheduling combines CFP and RAP resources. In principle, this structure can support both periodic and aperiodic traffic. However, a fixed hybrid superframe cannot adapt to changes in the network composition. If the number of periodic sources increases, an insufficient CFP can delay scheduled transmissions. If the number of aperiodic sources increases, an insufficient RAP can increase contention and retransmission. Conversely, an excessively large CFP or RAP can waste resources depending on the traffic composition.

Therefore, the main challenge in hybrid WBAN scheduling is not merely to use both CFP and RAP, but to adapt their placement and duration online according to the observed node composition and traffic regularity. This motivates an online superframe adaptation mechanism.

3.6. Our Approach: Online Collaborative Hybrid Scheduling

The proposed approach is designed to approximate the solution of **P1** without changing the underlying WBAN access structure. The central idea is to transform the heterogeneous scheduling problem into an online collaborative hybrid scheduling problem. At runtime, the coordinator estimates the traffic features of each source, classifies the source as periodic or aperiodic, and then assigns the source to an appropriate access mode.

The proposed framework is based on the following three principles.

(Principle 1) CFP-based age-aware scheduling for periodic traffic without retransmission.

For a periodic source, the coordinator estimates its sampling period and schedules its transmission slot as close as possible to the sampling start time. The purpose is to minimize the waiting time of each generated sample before transmission. In this CFP-based scheduling mode, retransmission is not allowed for periodic samples. This design choice is based on the observation that many periodic physiological streams have short sampling

intervals and are continuously observed over time. If a sample is lost, the next sample of the same stream will be generated soon. Therefore, allowing retransmission of an old periodic sample may consume slots that should be used for newer samples, causing buffer accumulation and rapid growth of sample-wise AoI. By contrast, dropping an outdated periodic sample and serving the next fresh sample can better preserve the timeliness of the continuous observation stream.

(Principle 2) RAP-based random access with retransmission for aperiodic traffic. For an aperiodic source, the coordinator cannot accurately predict when the next sample will be generated. Preallocating CFP slots to such a source can easily cause incorrect scheduling because the source may have no data at the reserved time. Therefore, the proposed framework does not reserve CFP slots for aperiodic sources. Instead, aperiodic sources contend for transmission opportunities in the RAP when they actually generate samples. Unlike periodic CFP traffic, retransmission is allowed for aperiodic traffic because an aperiodic sample may represent an irregular or event-driven observation. Losing such a sample cannot necessarily be compensated by a near-future periodic update.

(Principle 3) Online superframe adaptation. The proposed framework dynamically adapts the CFP/RAP composition of the superframe according to the runtime node composition. If more periodic sources are detected, more resources should be assigned to CFP-based scheduling. If more aperiodic sources are detected, sufficient RAP resources should be inserted to support random access. This online adaptation addresses the limitation of fixed hybrid scheduling, where the CFP/RAP partition remains unchanged even when the traffic composition varies.

From the perspective of mathematical novelty, the proposed method is not a simple heuristic that only aligns slots with sampling times. Instead, it provides an online approximation structure for the sample-wise weighted AoI minimization problem. The offline version of P1 requires complete knowledge of future sample generation times and exhaustive search over all feasible CFP/RAP configurations. Such information is unavailable in practical WBANs, and exhaustive search is computationally infeasible. The proposed online framework addresses this difficulty by using runtime traffic estimation and decomposing the original combinatorial problem into three tractable decisions: periodic source scheduling, aperiodic source access, and superframe adaptation.

This structure gives the proposed method a clear optimization-oriented interpretation. CFP-based scheduling approximates the optimal placement of periodic samples by reducing the distance between generation time and transmission time. RAP-based access avoids infeasible preallocation for unpredictable samples. Online superframe adaptation adjusts the feasible scheduling domain according to the observed traffic composition. Therefore, the proposed framework jointly mitigates incorrect scheduling, contention-induced delay, and non-adaptive resource partitioning, which are the main limitations of centralized, decentralized, and fixed hybrid scheduling approaches.

4. Extension of IEEE 802.15.6 Standard

The proposed online collaborative scheduler requires the coordinator and source nodes to share a common temporal reference. This is because the CFP-based scheduler attempts to allocate transmission slots close to the sampling start times of periodic sources. Without a common synchronization reference, the coordinator may incorrectly estimate the sampling instants of different sources, which can again cause empty-buffer scheduling or delayed transmission of fresh samples. Therefore, before applying the proposed scheduling algorithm, the initial sampling start times of the source nodes should be synchronized.

To support this requirement while preserving compatibility with the IEEE 802.15.6 superframe-based operation, we extend the beacon-based control procedure by introducing

a synchronization offset in the beacon frame. The purpose of this extension is not to change the medium access control (MAC) structure of IEEE 802.15.6, but to provide a lightweight synchronization reference that enables the coordinator to align scheduled CFP slots with the estimated sample generation times of periodic sources.

4.1. Synchronization Design and Implementation

To synchronize the initial sampling start times of the source nodes, we use the reserved 4-bit field in the IEEE 802.15.6 MAC generic frame format, as shown in Figure 2. The reserved field is interpreted as a *Synchronization Offset* field. This design does not introduce additional frame overhead because it reuses an existing reserved field.

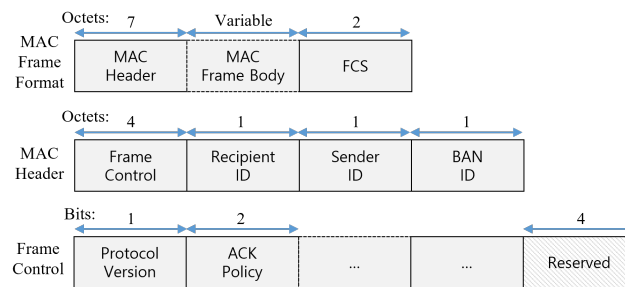


Figure 2. IEEE 802.15.6 generic MAC frame format.

The synchronization offset represents a time offset relative to the beacon transmission or reception reference. When a source receives the beacon frame, it extracts the synchronization offset and computes a common global reference time. Each source then aligns its first sampling operation with this reference time. After the initial synchronization, each periodic source continues sampling according to its own sampling period P_i , while the coordinator estimates and tracks this period at runtime.

4.2. Interrupt-Based Cross-Layer Synchronization

To reduce synchronization delay between the MAC layer and the application layer, an interrupt-based cross-layer signaling mechanism is used. When the MAC layer receives a beacon frame, it extracts the synchronization offset and computes the global reference time as

$$T_{\text{global}} = T_{\text{beacon}} + T_{\text{offset}}, \quad (13)$$

where T_{global} denotes the common reference time for synchronized sampling, T_{beacon} denotes the beacon reception timestamp, and T_{offset} denotes the synchronization offset value.

After computing T_{global} , the MAC layer generates a high-priority interrupt to notify the application layer. The application layer then configures the sensor hardware to start the next sampling operation at T_{global} . This mechanism enables source nodes to share a common temporal baseline while still allowing each source to follow its own sampling period. This synchronization procedure is essential for the proposed sample-wise age-aware scheduling because the scheduler attempts to reduce the time difference between the generation time $g_{i,k}$ of sample $u_{i,k}$ and its scheduled transmission time.

5. Age-Aware Collaborative Scheduling

The proposed scheduler is designed as an online collaborative hybrid scheduling framework for minimizing the sample-wise weighted AoI. The scheduler does not assume that all traffic patterns are known in advance. Instead, it extracts source-specific traffic features at runtime, classifies each source as periodic or aperiodic, and then determines whether the source should be served through CFP-based scheduled access or RAP-based contention.

This section describes the detailed operation of the proposed framework. The notation follows the sample-wise weighted AoI model introduced in Section 3.2. In particular, P_i , L_i , and W_i denote the sampling period, required transmission length, and priority weight of source i , respectively. The k -th sample generated by source i is denoted by $u_{i,k}$, and its generation time is denoted by $g_{i,k}$. The sample-wise AoI is denoted by $A_{i,k}^s(t)$, and the objective is to minimize the long-term weighted sum of $W_i A_{i,k}^s(t)$.

5.1. Basic Operations

As shown in Figure 3, the proposed method consists of the following three stages.

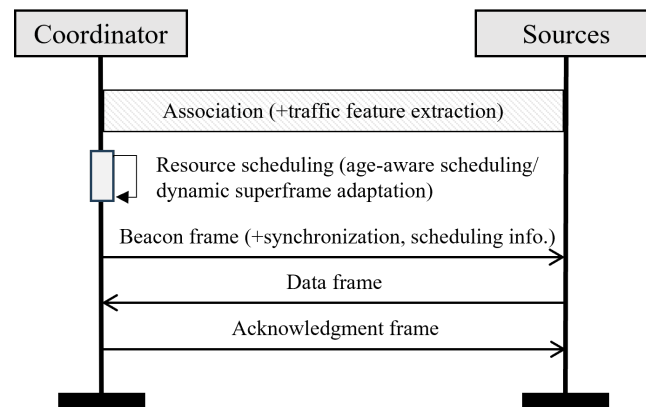


Figure 3. Sequence chart illustrating the basic operation of the proposed online collaborative scheduler.

(Stage 1) Association and traffic feature extraction. During the association phase, the coordinator collects traffic-related information from each source. The connection request frame provides the required transmission length L_i and the priority weight W_i . The coordinator then estimates the sampling period P_i at runtime by observing the sample reception pattern of the associated source. Based on the stability of the estimated sampling period, the coordinator classifies each source as either periodic or aperiodic.

(Stage 2) Online collaborative resource scheduling. After traffic feature extraction, the coordinator constructs the superframe by jointly considering CFP scheduling and RAP placement. Periodic sources are scheduled in the CFP because their sampling times can be estimated. The scheduler places their transmission slots close to the corresponding sampling start times to reduce $A_{i,k}^s(t)$. Aperiodic sources are not assigned pre-reserved CFP slots because their sample generation times are unknown. Instead, they are served through RAPs when they actually generate data.

(Stage 3) Beacon notification and data transmission. The coordinator broadcasts a beacon frame containing the synchronization reference and scheduling information. Periodic sources transmit their samples in the assigned CFP slots. Aperiodic sources contend for the RAP when they have generated samples. This operation jointly reduces empty-buffer scheduling in the CFP and unnecessary contention in the RAP.

5.2. Traffic Feature Extraction

The IEEE 802.15.6 standard specifies that the MAC management entity performs control-plane functions such as association, resource allocation, and beacon transmission. In the proposed framework, the coordinator uses this management procedure to extract traffic features without changing the basic superframe structure.

During association, each source transmits a connection request frame in the RAP. This frame contains the required transmission length L_i and the priority weight W_i of source i . After receiving the request, the coordinator assigns temporary dedicated uplink slots to the source in order to estimate its sampling behavior. Because these slots are

temporarily dedicated to the associated source, the queuing delay during this estimation phase is negligible.

Let r_t denote the reception time of a sample during the estimation phase. The corresponding sampling start time is estimated as

$$s_t = r_t - d_i, \quad (14)$$

where d_i is the expected transmission-related delay of source i . It is expressed as

$$d_i = e_i^{\text{queue}} + e_i^{\text{prop}} + e_i^{\text{tx}}, \quad (15)$$

where e_i^{queue} , e_i^{prop} , and e_i^{tx} denote the queuing delay, propagation delay, and transmission delay, respectively. During the temporary dedicated-slot estimation phase, e_i^{queue} is negligible because the source does not wait behind other sources. The term e_i^{prop} reflects the propagation delay between the source and the coordinator, and e_i^{tx} reflects the time required to transmit a sample of length L_i .

The sampling period estimate at time t is then obtained as

$$\hat{P}_{i,t} = s_t - s_{t-1}. \quad (16)$$

The coordinator determines whether source i is periodic by measuring the stability of $\hat{P}_{i,t}$. Let $\bar{P}_i$ be the average of the observed period estimates. The standard deviation is computed as

$$\sigma_i = \sqrt{\frac{1}{Q_i} \sum_{q=1}^{Q_i} (\hat{P}_{i,q} - \bar{P}_i)^2}, \quad (17)$$

where Q_i is the number of observed samples used for estimation. If σ_i is below a predefined threshold, source i is classified as periodic and assigned to the set $\mathcal{P}$. Otherwise, it is classified as aperiodic and assigned to the set $\mathcal{A}$. This classification is performed online and can be updated when the traffic pattern changes.

5.3. CFP-Based Age-Aware Scheduling for Periodic Sources

For periodic sources, the coordinator uses the estimated tuple (P_i, L_i, W_i) to construct the CFP schedule. The scheduling goal is to place the transmission opportunity of sample $u_{i,k}$ as close as possible to its generation time $g_{i,k}$. This directly reduces the sample-wise AoI term $W_i A_{i,k}^s(t)$ in the objective function.

Unlike conventional AoI schedulers that may select the source with the largest current node-level age, the proposed scheduler uses sample generation timing as an additional scheduling reference. Thus, a source is not scheduled simply because its age is large; it is scheduled when a new sample is expected to be available.

5.3.1. Retransmission Policy in the CFP

In the CFP-based scheduling mode, retransmission is not allowed for periodic samples. The proposed model assumes that many periodic physiological signals are continuously sampled streams with relatively short sampling intervals. If one sample is lost, the next sample of the same stream will be generated soon. Therefore, retransmitting an old periodic sample can consume the transmission opportunity of a newer sample, increase buffer accumulation, and rapidly increase the sample-wise AoI of subsequent samples.

Under this assumption, the proposed scheduler prioritizes timeliness of the continuous stream over reliable delivery of every individual periodic sample. A lost or outdated periodic sample is discarded, and the scheduler attempts to transmit the next fresh sample

near its sampling start time. This policy prevents retransmission-induced age divergence in the CFP and preserves the freshness of the ongoing observation stream.

5.3.2. Scheduling Rule and Preemption Utility

The coordinator first sorts periodic sources in descending order of their priority weights. For each periodic source, it attempts to allocate L_i consecutive CFP slots near each estimated sampling start time. If the desired slots are available, the slots are assigned to the corresponding sample. If the desired slots overlap with previously assigned slots, the scheduler shifts the allocation within the same sampling interval. If no feasible shifted position exists, the scheduler evaluates whether preemption is beneficial.

Let I_i^k denote the first slot index assigned to the k -th scheduled sample of source i . The priority-weighted gain of assigning source i closer to its desired sampling time is defined as

$$\gamma_{\text{gain}} = (I_i^k - I_i^{k-1})W_i. \quad (18)$$

If source i preempts a slot already assigned to source j , the corresponding priority-weighted loss is defined as

$$\gamma_{\text{loss}} = (I_j^{k+1} - I_j^{k-1})W_j. \quad (19)$$

The preemption utility is then given by

$$U_i = \gamma_{\text{gain}} - \gamma_{\text{loss}}. \quad (20)$$

The scheduler allows preemption only when $U_i > 0$. This rule approximates the reduction of the sample-wise weighted AoI objective by accepting preemption only when the expected weighted freshness gain is larger than the weighted loss imposed on the already scheduled source.

Algorithm 1 implements the CFP-based age-aware scheduling rule. The algorithm is an online heuristic approximation of the sample-wise weighted AoI minimization problem. It does not attempt exhaustive search over all possible CFP configurations. Instead, it greedily constructs a priority-aware and sampling-aware schedule using the currently estimated traffic features.

Algorithm 1 CFP-Based Age-Aware Scheduling for Periodic Sources

Input:

- Periodic source set $\mathcal{P}$.
- Estimated traffic parameters (P_i, L_i, W_i) for each $i \in \mathcal{P}$.
- Uplink allocation vector V with length $V_{\max}$.

Output:

- CFP slot allocation vector V .
1. Sort sources in $\mathcal{P}$ in descending order of W_i .
 2. For each source $i \in \mathcal{P}$, repeat the following steps.
 3. For each estimated sampling start time $g_{i,k}$ within the scheduling horizon:
 - (a) Search for L_i consecutive empty slots closest to $g_{i,k}$.
 - (b) If such slots exist, allocate them to sample $u_{i,k}$.
 - (c) Otherwise, shift the candidate allocation within the interval $[g_{i,k}, g_{i,k+1})$.
 - (d) If no feasible shifted position exists, compute U_i using (20).
 - (e) If $U_i > 0$, preempt the overlapping slots and allocate them to $u_{i,k}$.
 - (f) Otherwise, skip the current sample and wait for the next sample.
-

5.4. Online Superframe Adaptation for Aperiodic Sources

The CFP schedule alone cannot support aperiodic traffic efficiently because the generation times of aperiodic samples are unknown in advance. If the coordinator preallocates CFP slots to aperiodic sources, these slots may remain unused when no sample is generated. This recreates the incorrect scheduling problem. Therefore, the proposed framework serves aperiodic sources through RAPs.

Unlike the fixed hybrid approach, where the CFP/RAP partition is predetermined, the proposed method adapts the RAP placement and duration according to the runtime node composition. If more aperiodic sources are detected, more RAP resources should be inserted. If periodic sources dominate the network, the RAP portion should be reduced to avoid unnecessary contention resources.

RAP Placement Rule

The coordinator inserts RAPs into the superframe after constructing the CFP allocation for periodic sources. Because inserting RAPs may shift or remove scheduled CFP slots, the coordinator selects RAP positions that minimize the expected weighted loss imposed on the periodic schedule.

For a candidate RAP insertion starting at slot t with length L_i , the loss score is defined as

$$S_{\text{loss}}(t) = \sum_{m=t}^{t+L_i-1} \gamma_{\text{loss}}(m), \quad (21)$$

where $\gamma_{\text{loss}}(m)$ denotes the weighted loss caused by using slot m as a RAP slot instead of a scheduled CFP slot. The optimal RAP insertion position is determined as

$$P_{\text{opt}} = \arg \min_t S_{\text{loss}}(t). \quad (22)$$

This rule inserts RAPs into positions where the disruption to periodic traffic is minimized.

Algorithm 2 addresses the limitation of fixed hybrid scheduling by adapting the CFP/RAP structure online. It preserves scheduled resources for periodic traffic as much as possible while providing random access opportunities for aperiodic traffic.

Algorithm 2 Online Superframe Adaptation

Input:

- Current allocation vector V .
- Aperiodic source set $\mathcal{A}$.
- Required slot length L_i and priority weight W_i for each $i \in \mathcal{A}$.

Output:

- Updated CFP/RAP allocation vector V .
1. Sort sources in $\mathcal{A}$ in descending order of L_i or W_i .
 2. For each source $i \in \mathcal{A}$:
 - (a) For each candidate RAP position t , compute $S_{\text{loss}}(t)$ using (21).
 - (b) Determine P_{opt} using (22).
 - (c) Insert an RAP of length L_i at P_{opt} .
 - (d) Update the allocation vector V .
-

5.5. RAP-Based Priority Backoff and Retransmission

Aperiodic samples may correspond to irregular or event-driven observations. Unlike periodic streams, an aperiodic sample may not be replaced by another fresh sample in the near future. Therefore, retransmission is allowed for aperiodic traffic in the RAP.

When multiple aperiodic sources contend in the RAP, collisions may occur. To reduce collision-induced delay for important traffic, we use a priority-based dynamic backoff rule. A source with a larger priority weight W_i selects a smaller initial backoff window and experiences a smaller backoff increase after collision. This gives high-priority aperiodic samples more frequent access opportunities.

Algorithm 3 gives an optimization-oriented role to the decentralized component. It does not merely provide random access; rather, it biases the contention process toward high-priority aperiodic samples, thereby reducing their expected contribution to the weighted sample-wise AoI. If a collision occurs, retransmission is attempted up to $BO_{\max}$ times. This policy explicitly addresses packet loss in the RAP, while avoiding retransmission-induced age growth in the CFP for periodic traffic.

Algorithm 3 RAP-Based Priority Backoff with Retransmission

Input:

- Priority weight W_i and required slot length L_i of aperiodic source i .
- Available RAP length L_{RAP} .
- Maximum backoff window $B_{\max}$.
- Maximum allowable retransmission attempts $BO_{\max}$.

1. Initialize the backoff counter as

$$BO_i \leftarrow \text{Random}\left(0, \frac{B_{\max}}{W_i}\right).$$

2. Initialize the retransmission attempt counter as

$$\text{attempts}_i \leftarrow 0.$$

3. Repeat until the sample is transmitted or dropped:

- (a) Wait for BO_i slots.
- (b) If $L_{\text{RAP}} \geq L_i$ and the RAP is available, transmit the sample.
- (c) If collision or RAP unavailability occurs, update

$$\text{attempts}_i \leftarrow \text{attempts}_i + 1.$$

- (d) If $\text{attempts}_i > BO_{\max}$, drop the sample.
- (e) Otherwise, update the backoff counter as

$$BO_i \leftarrow \text{Random}\left(0, BO_i \left(1 + \frac{1}{W_i}\right)\right).$$

5.6. Computational Complexity

The proposed framework consists of three algorithmic components: traffic feature extraction, CFP-based age-aware scheduling, and online superframe adaptation with RAP-based backoff.

For traffic feature extraction, each source uses Q_i observed samples to estimate the sampling period and its standard deviation. The complexity for source i is $O(Q_i)$, and the total complexity is $O(\sum_{i \in \mathcal{N}} Q_i)$.

For CFP-based age-aware scheduling, the coordinator examines candidate slot positions for periodic sources. If $V_{\max}$ denotes the number of uplink slots in the scheduling vector and $|\mathcal{P}|$ denotes the number of periodic sources, the worst-case search complexity is $O(|\mathcal{P}|V_{\max}^2)$ when shifting and preemption checks are required. In typical operation, where the search is restricted to the interval between two consecutive sampling instants, the practical complexity is lower.

For online superframe adaptation, the coordinator evaluates candidate RAP insertion positions. If $|\mathcal{A}|$ denotes the number of aperiodic source types considered for RAP insertion, the complexity is $O(|\mathcal{A}|V_{\max})$ when the loss score is updated incrementally. The RAP-based backoff algorithm is executed locally at each aperiodic source. Its worst-case number of attempts is bounded by $BO_{\max}$, giving a per-sample complexity of $O(BO_{\max})$.

Therefore, the proposed framework avoids exhaustive search over all feasible CFP/RAP configurations and provides a polynomial-time online approximation structure. This complexity analysis supports the suitability of the proposed method for practical WBAN operation and addresses the need to report the processing overhead required to achieve lower sample-wise weighted AoI.

6. Performance Evaluation

In this section, we evaluate the proposed online collaborative scheduling framework through NS-3 simulations. The main objective is to verify whether the proposed method reduces the sample-wise weighted AoI under heterogeneous WBAN traffic conditions. In addition to the main AoI results, we analyze the superframe utilization ratio and the number of collisions to explain the scientific reasons behind the performance improvement. We also provide a computational complexity analysis to clarify the additional processing cost required by the proposed online scheduling framework.

6.1. Simulation Setting

The proposed scheme was implemented using the NS-3 network simulator. The simulated WBAN consists of one coordinator and multiple heterogeneous source nodes connected through a one-hop star topology. The coordinator operates in beacon mode with a superframe structure. Periodic sources are served through the CFP, whereas aperiodic sources are served through the RAP.

Table 3 summarizes the source-level traffic configuration used in the simulations. Types 1–3 generate periodic data streams, where the sampling period P_i is randomly selected within the corresponding range. Types 4–6 generate aperiodic data streams and therefore do not have a fixed sampling period. The parameter L_i denotes the number of slots required to transmit one sample, and W_i denotes the priority weight of source type i . The table also clarifies the access mode and retransmission policy used for each traffic type. For periodic sources, retransmission is not allowed in the CFP because a newly generated sample is expected to arrive soon and retransmitting an outdated sample can delay newer samples. For aperiodic sources, retransmission is allowed in the RAP because an event-driven sample may not be replaced by another near-future sample.

Table 3. Source specifications and access policies.

Type	P_i (slots)	L_i (slots)	W_i	Traffic	Access/Retransmission
1	30–50	1	1	Periodic	CFP/No retransmission
2	20–30	2	3	Periodic	CFP/No retransmission
3	5–10	3	7	Periodic	CFP/No retransmission
4	–	1	1	Aperiodic	RAP/Retransmission allowed
5	–	2	3	Aperiodic	RAP/Retransmission allowed
6	–	3	7	Aperiodic	RAP/Retransmission allowed

Initially, the coordinator does not know the exact sampling period of each source. Therefore, it estimates P_i through runtime traffic feature extraction. A source is classified as periodic if the estimated sampling period reaches a steady state; otherwise, it is classified

as aperiodic. The simulation was executed for 3600 s and repeated 100 times with a 95% confidence interval.

To examine the effect of network composition, we consider two representative traffic scenarios. In the periodic-dominant scenario, the ratio between periodic and aperiodic sources is set to 4:1. For example, when 100 sources are deployed, 80 sources are selected from Types 1–3, and 20 sources are selected from Types 4–6. In the aperiodic-dominant scenario, the ratio is reversed to 1:4. These two scenarios allow us to evaluate whether the proposed online superframe adaptation can respond to different CFP/RAP demands. The main simulation parameters are summarized in Table 4.

Table 4. Simulation parameters.

Parameter	Value
Simulator	NS-3
Network topology	One-hop star topology
Frequency band	868 MHz
Modulation	ASK
Data rate	250 Kbps
Access mode	Beacon-enabled superframe
Scheduled access region	CFP/MAP-based allocation
Random access region	RAP/EAP-based contention
Transmission power	0 dBm
Reception sensitivity	−82 dBm
Beacon period	255 ms
ACK mode	I-ACK
Mobility model	Random
Number of sources	Variable
Simulation time	3600 s
Repetitions	100
Confidence interval	95%
CFP retransmission policy	Not allowed for periodic samples
RAP retransmission policy	Allowed for aperiodic samples
Main evaluation metrics	Sample-wise weighted AoI, source-wise AoI, utilization, collisions

6.2. Benchmark Schemes

The proposed method is compared with two representative AoI-aware scheduling schemes.

(1) Centralized AoI scheduler [32]: In this scheme, the coordinator examines the current AoI values of all sources and schedules the source that is expected to provide the largest age reduction. This benchmark represents centralized AoI-aware scheduling based mainly on age values. Since it does not explicitly distinguish whether a newly generated sample is available at the scheduled source, it can suffer from incorrect scheduling under heterogeneous sampling periods.

(2) Decentralized AoI scheduler [33]: In this scheme, each source determines its transmission probability or backoff behavior based on its local AoI. A source with a larger AoI obtains a higher chance of channel access. This benchmark represents decentralized AoI-aware random access. Since all sources may participate in contention, collision and backoff overhead can increase as the number of sources grows.

(3) Proposed online collaborative scheduler: The proposed scheduler estimates the traffic pattern of each source at runtime. Periodic sources are served through CFP-based age-aware scheduling, where slots are placed near the sampling start times. Aperiodic

sources are served through RAP-based random access. The CFP/RAP composition is adapted online according to the detected source composition.

6.3. Evaluation Metrics and Analytical Interpretation

To avoid relying only on the final AoI values, we evaluate the proposed scheduler using both objective and explanatory performance metrics. The primary objective metric is the sample-wise weighted AoI, which corresponds to the optimization objective defined in Section 3.2. In addition, we analyze the superframe utilization ratio and the number of collisions as explanatory metrics. The superframe utilization ratio indicates how effectively the allocated CFP slots are used for actual data transmission and therefore reflects the severity of the incorrect scheduling problem. The number of collisions indicates the contention overhead in RAP-based access and explains the AoI increase caused by decentralized random access.

For a generated sample $u_{i,k}$, the sample-wise AoI is determined by the time difference between its generation time and delivery time. Therefore, reducing the waiting time before transmission or reducing collision-induced delay directly reduces the weighted term $W_i A_{i,k}^s(t)$. The proposed scheduler is expected to reduce this value in two ways. First, it improves CFP utilization by assigning scheduled slots mainly to periodic sources whose sampling instants can be estimated. Second, it reduces RAP contention by preventing predictable periodic sources from unnecessarily competing in random access. These two mechanisms are validated through the utilization and collision results.

6.4. Traffic Classification Accuracy

Figure 4 shows the average miss ratio of the proposed traffic classification scheme. Sources of Types 1–3 exhibit relatively low miss ratios because they generate periodic data streams whose sampling periods converge to stable values. In contrast, Sources of Types 4–6 show high miss ratios because their traffic generation does not converge to a fixed sampling period. The coordinator therefore classifies them as aperiodic sources.

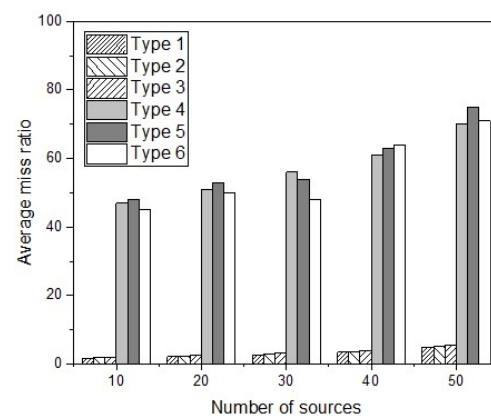


Figure 4. Average miss ratio of the proposed traffic classification scheme.

This result validates the first step of the proposed online collaborative scheduler. Accurate classification of periodic sources is important because these sources are assigned CFP slots. Aperiodic sources should not be assigned pre-reserved CFP slots because doing so can recreate the incorrect scheduling problem. Therefore, the classification result supports the proposed separation between CFP-based periodic scheduling and RAP-based aperiodic access.

6.5. Sample-Wise Weighted AoI

Figure 5 compares the sample-wise weighted AoI of the proposed scheduler with those of the centralized and decentralized benchmarks. The centralized scheduler shows poor performance when traffic heterogeneity increases. This is because it schedules sources mainly according to AoI values without explicitly considering whether a new sample is available. As a result, it can assign CFP slots to sources with empty buffers, causing resource waste and increasing the sample-wise weighted AoI.

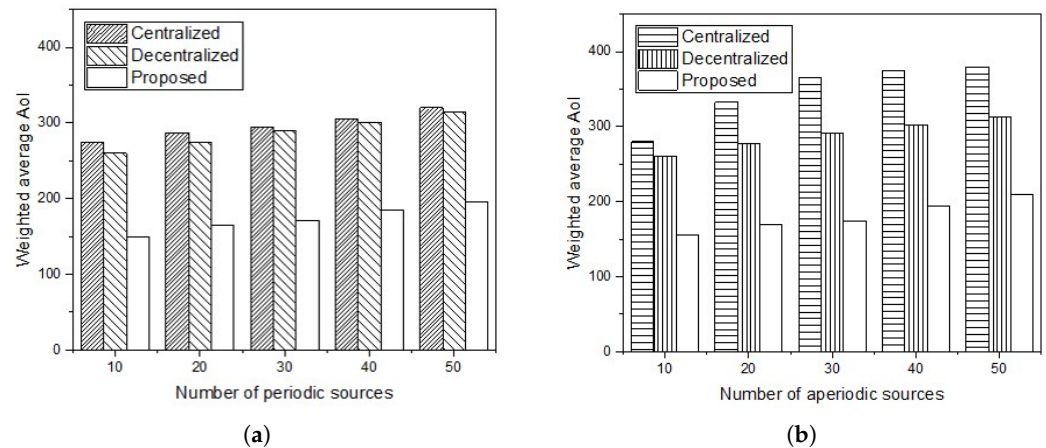


Figure 5. Performance comparison: sample-wise weighted AoI. (a) Impact of varying number of periodic sources. (b) Impact of varying number of aperiodic sources.

The decentralized scheduler performs better than the centralized scheduler when the network load is low or when aperiodic sources dominate. This is because sources contend only when they have data to transmit, which naturally avoids empty-buffer scheduling. However, as the number of sources increases, the decentralized scheduler suffers from frequent collisions and backoff delays. These delays postpone successful delivery of generated samples and increase their sample-wise AoI.

The proposed scheduler achieves the lowest sample-wise weighted AoI in both scenarios. This is because it jointly addresses the weaknesses of the centralized and decentralized benchmarks. Periodic sources are scheduled near their sampling start times, which reduces the waiting time of generated samples. Aperiodic sources use RAPs only after generating data, which avoids pre-reservation waste. Moreover, online superframe adaptation balances CFP and RAP resources according to the source composition.

6.6. Superframe Utilization and Collision Analysis

Figure 6a provides an explanatory result for the AoI improvement shown in Figure 5. The superframe utilization ratio measures the fraction of allocated transmission resources that are actually used for data delivery. A low utilization ratio indicates that the scheduler frequently assigns slots to sources without newly generated samples, which corresponds to the incorrect scheduling problem.

The centralized scheduler suffers from this issue because it makes scheduling decisions mainly based on AoI values without explicitly considering sample availability. In contrast, the proposed scheduler estimates traffic regularity at runtime and assigns CFP slots mainly to periodic sources whose sampling instants can be predicted. Therefore, more allocated slots are used for actual sample transmission, resulting in a lower sample-wise weighted AoI.

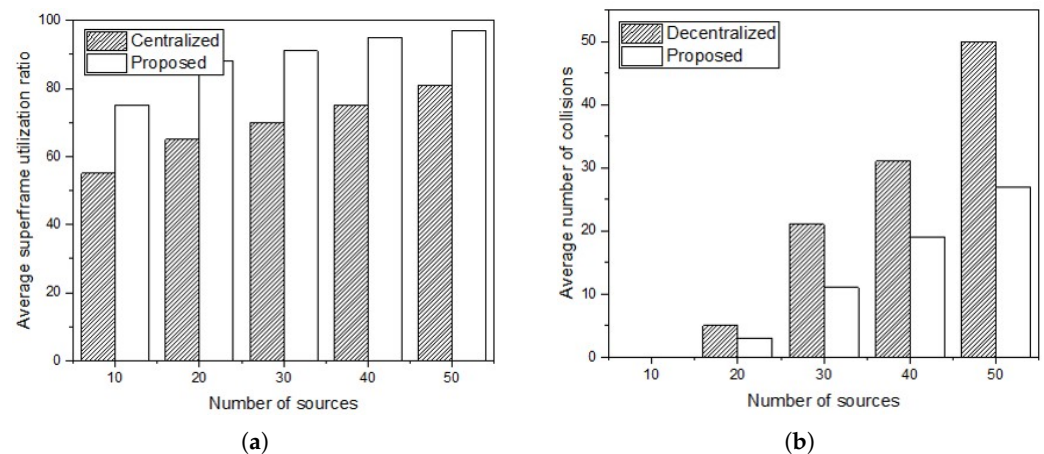


Figure 6. Performance comparison: average superframe utilization ratio and average number of collisions. (a) Superframe utilization ratio. (b) Number of collisions.

Figure 6b explains the limitation of decentralized AoI scheduling. The number of collisions increases as more sources contend for RAP access. Although decentralized scheduling can avoid empty-buffer scheduling, excessive contention increases backoff delay and postpones the successful delivery time of generated samples. Since the sample-wise AoI is determined by the time difference between sample generation and delivery, collision-induced delay directly increases the weighted AoI.

The proposed scheduler reduces this effect by preventing predictable periodic sources from unnecessarily joining RAP contention. As a result, the number of contenders is reduced, which leads to fewer collisions and lower AoI. This result also supports the design choice that periodic traffic should be served through CFP-based scheduling, whereas RAP resources should be mainly reserved for aperiodic traffic.

6.7. Source-Wise AoI for High-Priority Sources

Figure 7 compares the source-wise average AoI of the centralized, decentralized, and proposed schedulers. The result is particularly important for high-priority sources, such as Types 3 and 6, because their priority weights are larger than those of the other source types.

In the centralized scheduler, high-priority sources may still suffer from increased AoI when their sampling behavior is not aligned with the assigned slots. This occurs because high priority alone does not guarantee that a fresh sample exists at the scheduled time. In the decentralized scheduler, high-priority sources obtain more frequent access opportunities, but their AoI may still increase under heavy contention because of collision and backoff delay.

The proposed scheduler reduces the AoI of high-priority sources by applying different mechanisms according to traffic type. For high-priority periodic sources, CFP slots are arranged near their sampling start times. For high-priority aperiodic sources, RAP access is provided without pre-reserving CFP slots that may remain unused. Therefore, the proposed method improves source-wise AoI not simply by prioritizing high-weight sources, but by combining priority with traffic regularity and access-mode selection.

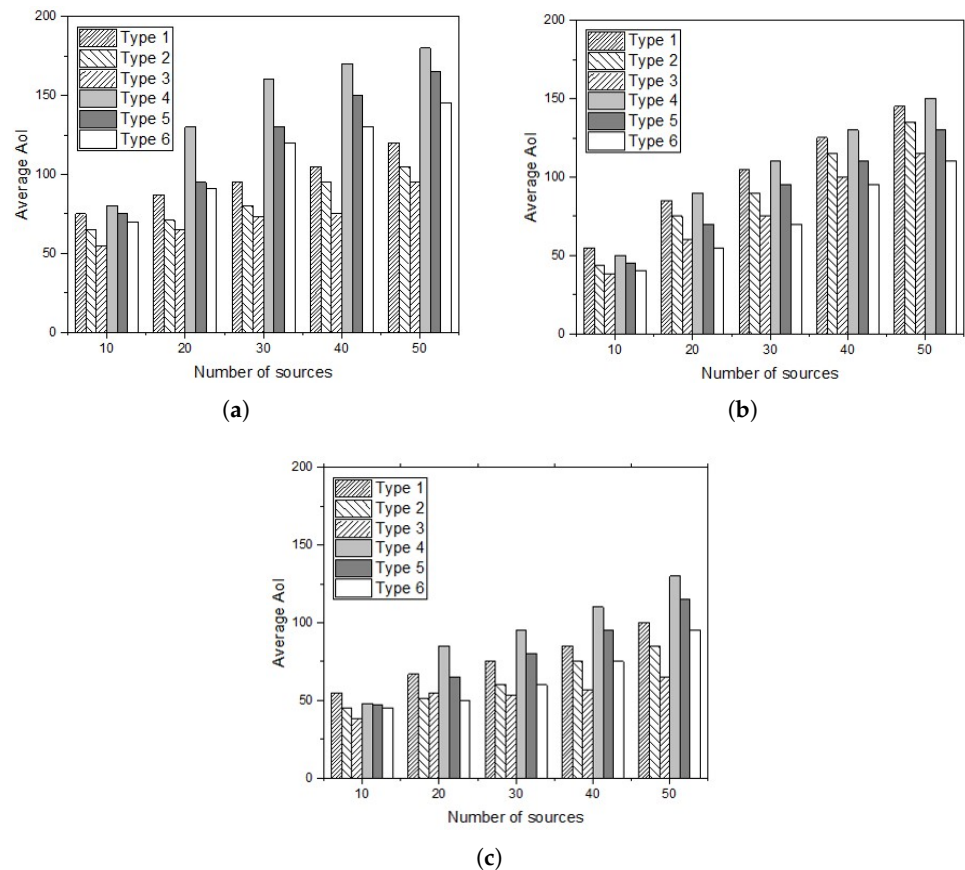


Figure 7. Performance comparison: source-wise average AoI. (a) Centralized. (b) Decentralized. (c) Collaborative (proposed).

6.8. Computational Complexity Analysis

In addition to the simulation results, we analyze the computational complexity of the proposed scheduler to clarify the processing overhead required to obtain the AoI improvement. Let $V_{\max}$ denote the number of uplink allocation slots in a superframe, $|\mathcal{P}|$ denote the number of periodic sources, and $|\mathcal{A}|$ denote the number of aperiodic source types.

The traffic feature extraction step estimates the sampling period of each source using Q_i observed samples. Thus, its complexity is $O(\sum_{i \in \mathcal{N}} Q_i)$. The CFP-based age-aware scheduling algorithm searches feasible slot positions for periodic sources and may perform shifting and preemption checks. Its worst-case complexity is $O(|\mathcal{P}|V_{\max}^2)$. The online superframe adaptation algorithm searches candidate RAP insertion positions and computes the loss score for each candidate position. Its complexity is $O(|\mathcal{A}|V_{\max})$ when the loss score is updated incrementally. The priority-based backoff procedure is executed locally at each aperiodic source and is bounded by the maximum number of backoff attempts, resulting in $O(BO_{\max})$ per aperiodic sample.

Table 5 summarizes the computational complexity of the proposed components and the benchmark schedulers. The proposed scheduler introduces additional computation compared with simple centralized or decentralized rules, but it avoids exhaustive search over all possible CFP/RAP configurations. Therefore, the proposed scheduler provides a polynomial-time online approximation structure for reducing the sample-wise weighted AoI under heterogeneous WBAN traffic.

Table 5. Summary of computational complexity.

Component/Scheme	Main Operation	Complexity
Traffic feature extraction	Period estimation and classification	$O(\sum_{i \in \mathcal{N}} Q_i)$
CFP age-aware scheduling	Slot search, shifting, preemption	$O(\mathcal{P} V_{\max}^2)$
Online superframe adaptation	RAP insertion search	$O(\mathcal{A} V_{\max})$
RAP priority backoff	Local retransmission attempts	$O(BO_{\max})$ per sample
Centralized benchmark	Slot-by-slot age comparison	$O(NV_{\max})$
Decentralized benchmark	Local contention decision	$O(BO_{\max})$ per sample

6.9. Discussion

The results show that the proposed scheduler improves AoI performance because it addresses two different causes of information staleness. The first cause is resource waste due to incorrect scheduling. This is observed through the superframe utilization ratio. When slots are allocated to sources without newly generated samples, the utilization ratio decreases and generated samples from other sources remain stale. The proposed scheduler reduces this effect by assigning CFP slots mainly to periodic sources whose sampling instants are estimated at runtime.

The second cause is contention-induced delay. This is observed through the number of collisions. Decentralized access avoids empty-buffer scheduling but increases the collision probability when many sources compete simultaneously. The proposed scheduler reduces this effect by separating periodic and aperiodic traffic and limiting RAP contention mainly to aperiodic sources.

The complexity analysis further shows that the proposed method improves AoI without requiring exhaustive search over all feasible superframe configurations. Although the proposed framework requires additional computation for traffic feature extraction, CFP slot placement, and RAP insertion, these procedures remain polynomial in the number of sources and the superframe length. Therefore, the proposed method provides a practical online approximation structure for sample-wise weighted AoI minimization in heterogeneous WBAN-based healthcare monitoring systems.

7. Conclusions

This paper addressed the sample-wise weighted AoI minimization problem in heterogeneous WBAN-based healthcare monitoring systems by focusing on the structural limitations of three representative AoI-aware resource allocation approaches. Centralized scheduling can provide controllable slot allocation but may cause incorrect scheduling when slots are assigned to sources without newly generated samples. Decentralized access can avoid such empty-buffer scheduling but may increase collision and backoff delay when many sources contend for the channel. Fixed hybrid access can combine scheduled and random access, but it may waste resources when the ratio of periodic and aperiodic traffic changes. To jointly overcome these limitations, we proposed an online collaborative hybrid scheduler that extracts traffic features at runtime, separates periodic and aperiodic sources, schedules periodic samples through contention-free access near their sampling start times, and serves aperiodic samples through random access without pre-reserving resources. The proposed scheduler also adapts the contention-free and random access regions according to the observed traffic composition. Simulation results showed that the proposed method reduces sample-wise weighted AoI compared with representative centralized and decentralized AoI schedulers. The superframe utilization analysis confirmed that the proposed method mitigates incorrect scheduling, while the collision analysis showed that separating periodic and aperiodic traffic reduces contention-induced delay. The complexity

analysis further showed that the proposed method provides a polynomial-time online approximation structure without exhaustive search over all feasible superframe configurations. Future work will extend this framework by incorporating detailed interference-aware channel models, adaptive retransmission control, and theoretical performance bounds for online sample-wise AoI minimization.

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