

Optimal Message Bundling with Delay and Synchronization Constraints in Wireless Sensor Networks

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Abstract—Message bundling is an effective way to reduce the energy consumption for message transmissions in wireless sensor networks. However, bundling more messages could increase both end-to-end delay and message transmission interval; the former needs to be maintained within a certain value for time-sensitive applications like environmental monitoring, while the latter affects time synchronization accuracy when the bundling includes synchronization messages as well. Taking as an example a novel time synchronization scheme recently proposed for energy efficiency, we propose an optimal message bundling approach to reduce the message transmissions while maintaining the user-defined requirements on end-to-end delay and time synchronization accuracy. Through translating the objective of joint maintenance to an integer linear programming problem, we compute a set of optimal bundling numbers for the sensor nodes to constrain their link-level delays, thereby achieve and maintain the required end-to-end delay and synchronization accuracy while the message transmission is minimized.

Index Terms—Energy efficiency, message bundling, end-to-end delay, time synchronization accuracy, wireless sensor networks.

I. INTRODUCTION

In the typical wireless sensor networks (WSNs), with a view to the energy capacity and the serve time, minimizing energy consumption is utmost critical. Considering the radio activities consume the most energy in the sensor node, reducing the number of message transmissions in the sensor network is considered as a major approach of energy conservation, in which an efficient way is the data bundling¹ [1]. Depending on the operation locations, the existing data bundling schemes (e.g., [2]–[4]) could be classified to in-node, in-network and hybrid bundling. However, one common negative impact of employing the data bundling procedure is the increasing of end-to-end (E2E) delay. By E2E delay, we mean the difference between the time of measurement (T_m^s) at an originating sensor node and the time of the reception of the resulting measurement data by the head node (T_m^r) via a message as demonstrated in Fig. 1. Nevertheless, for most monitoring

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¹The terms of “data bundling” and “message bundling” are used interchangeably in this paper.

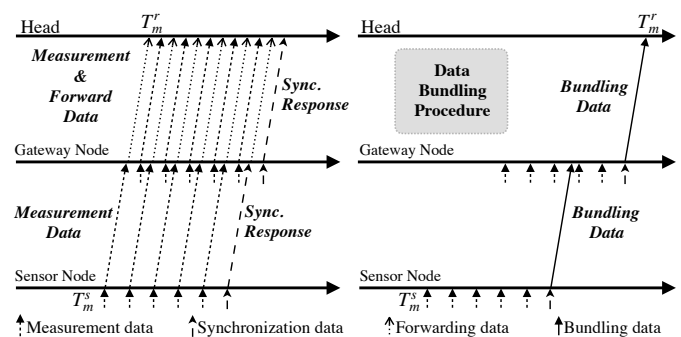


Fig. 1. Comparison of the message transmissions of the time synchronization schemes with and without data bundling procedure.

applications in WSNs, time synchronization is also critical for ordering the measurement data and detecting the events. Consequently, optimally bundling the transmission messages with maintaining the E2E delay and the time synchronization accuracy is in demand, which is not considered in the existing data bundling schemes.

On the basis of the novel energy-efficient time synchronization scheme [5]—called EE-ASCFR throughout the paper—which proposes data bundling as an optional procedure for reducing energy consumption, the time synchronization could be realized without heavy consumption on the energy and computing resources. In EE-ASCFR, because synchronization messages are embedded in measurement data report messages from sensor nodes to reduce the number of message transmissions, the synchronization interval (SI) is tied to the interval of report messages for measurement data. Bundling more data, therefore, could reduce more energy consumption for message transmissions, but it could not only increase E2E delay but also worsen synchronization accuracy due to the increased SI as discussed in [5]. In such a case, we need to optimize the number of bundled messages under the constraint of E2E delay and time synchronization accuracy in achieving higher energy efficiency.

In this paper, we formulate the aforementioned bundling

Response Message	#1 Measurement Timestamp + Data	...	#N Measurement Timestamp + Data
$T_1, T_2, T_3, \#Seq$	T_m^1, m^1		T_m^N, m^N

Fig. 2. Payload contents of the data bundling procedure introduced in EE-ASCFR [5].

TABLE I
MAE AND MSE OF MEASUREMENT TIME ESTIMATION OF EE-ASCFR AND AHTS WITH DIFFERENT SIS PROVIDED IN [5] AND [7]

Synchronization Scheme		MAE ¹	MSE ²
EE-ASCFR	SI = 100 s	8.8811E-25	5.8990E-19
	SI = 1 s	9.1748E-25	5.4210E-19
	SI = 10 ms	1.0887E-24	4.7684E-19
AHTS	SI = 100 s	8.4225E-06	1.2524E-10
	SI = 10 s	2.3385E-06	9.1694E-12
	SI = 1 s	1.8166E-06	5.2094E-12

¹ MAE is the mean absolute error of measurement time estimation.

² MSE is the mean square error of measurement time estimation.

optimization problem as integer linear programming (ILP), where the number of bundled messages for each sensor node is optimized while jointly satisfying the user-defined performance requirements on E2E delay and time synchronization accuracy. In this way, we can further reduce the energy consumption through data bundling while meeting the requirements.

The rest of the paper is organized as follows: Section II introduces the time synchronization scheme based on the data bundling procedure as well as the related conflicts of performance metrics. Section III presents our proposed approach and its formulation as ILP. Section IV exhibits our system design at both head² and sensor node. Section V demonstrates the performance of the proposed approach through experimental results on a real WSN testbed. Section VI concludes our work in this paper and discusses the future works.

II. PRELIMINARIES

Most WSNs have the fundamental characteristics of limited resources, multi-hop communication, large scale and dynamic environments [6]. To achieve satisfactory performance in typical WSN applications including environmental monitoring, event detection and industrial applications, several specific requirements—e.g., E2E delay and synchronization accuracy—have to be met. With consideration to the most basic requirement of energy efficiency, joint maintaining the three metrics are crucial.

A. Energy-Efficient Time Synchronization Schemes Using Data Bundling

To fulfill the desired requirements of energy efficiency and synchronization accuracy, many schemes have been proposed such as [5], [8], [9]. Among those, EE-ASCFR proposed in [5] particularly suits the E2E delay calculation since computing

²The head node and the PC or server connected to it are jointly called as head throughout this paper.

the E2E delay at the head is completely in conformity with the preferential asymmetric scenario of EE-ASCFR. However, because the synchronization accuracy (SA) is affected by SI as illustrated in Table I (i.e., simulation results of EE-ASCFR and practical evaluation results of AHTS [7]), we need to maintain SI to a reasonable value for better synchronization accuracy. Based on those evaluation results in Table I, the relationship (\mathcal{T}) between SI and synchronization accuracy is represented as follows:

$$SI = \mathcal{T}(SA), \quad (1)$$

in which the requirement of SA could be translated to the requirement of SI.

To further reduce energy consumption, EE-ASCFR also employs data bundling: In downstream, the synchronization “Request” message for timestamp T_1 is embedded inside a regular beacon message; in upstream, the synchronization “Response” message for timestamps T_1 , T_2 , and T_3 are bundled together with measurement data as shown in Fig. 2. Note that bundling more measurement data could lead to better energy efficiency, which, however, increases SI and decreases SA as discovered in the evaluation of [5] and [7]. Nevertheless, as EE-ASCFR only covers the single-hop scenario, the more asymmetric approach (i.e., AHTS), which is based on EE-ASCFR and extends it to multi-hop resource-constrained sensor networks, is employed in the proposed approach to cover multi-hop scenarios. The data bundling procedure is inherited and extended to the multi-hop case as illustrated in Fig. 1.

B. Conflicts of Performance Metrics: Energy Efficiency, E2E Delay and Synchronization Accuracy

Simultaneously meeting the requirements for the three performance metrics of energy efficiency, E2E delay, and synchronization accuracy is not possible due to their relationship discussed in Section II-A. Time synchronization provides the possibility of accurate calculation and maintenance of E2E delay, and employing the time synchronization scheme requires certain computing and power resources, which turns out the *conflict between energy efficiency and E2E delay calculation*. Although the data bundling procedure introduced in EE-ASCFR could drastically reduce the energy consumption for message transmissions and bundling more data could lead to higher energy efficiency, the data bundling procedure could direct result in high E2E delay as exhibited in Fig. 1, which is the *conflict between energy efficiency and E2E delay maintenance*. Specific to the delay calculation illustrated in Fig. 1, the E2E delay—i.e., $T_m^r - T_m^s$ —of measurement m , would be relatively small (e.g., multiples of forwarding delay which typically in milliseconds) in the regular direct forwarding method. However, due to the bundling procedure in the intermediate sensor nodes, the E2E delay could be as large as multiples of measurement interval. Nonetheless, the bundling procedure is shown to be quite efficient in conserving energy by reducing the number of message transmissions as shown in Fig. 1, which is critical to low-power sensor nodes.

As for synchronization accuracy, SI should be shorter for achieving higher accuracy [5], but shorter SI results in more message transmissions, which again leads to higher energy consumption. This draws forth the *conflict between energy efficiency and synchronization accuracy*. To jointly meet the three performance requirements, comprehensive optimizations should be taken. To yield comprehensive satisfactory performances among those three requirements, a new approach for the bundling number optimization for each sensor node is proposed to fulfill the requirement of maintaining E2E delay and synchronization accuracy while minimizing the message transmissions.

III. ILP MODEL FOR OPTIMAL BUNDLING PROBLEM

In a WSN with N sensor nodes, the energy consumption e_i^t for the message transmissions at sensor node i is modeled as follows: For $i \in [0, 1, \dots, N-1]$,

$$e_i^t = \alpha_i e_i^m + \beta_i e_i^s + \gamma_i e_i^f, \quad (2)$$

where e_i^m and e_i^s denote the energy consumption for the transmission of a measurement and a synchronization message generated by sensor node i respectively, and e_i^f is the energy consumption for forwarding either a synchronization or a measurement message from offspring sensor nodes at sensor node i . The coefficients α_i , β_i and γ_i are the number of transmissions for corresponding messages.

If we apply data bundling, (2) can be modified as follows:

$$e_i^t = \begin{cases} \delta_i e_i^b, & \text{all data bundling} \\ \delta_i e_i^b + \gamma_i e_i^f, & \text{self data bundling} \end{cases} \quad (3)$$

where $\delta_i e_i^b$ is the total energy consumption caused by transmitting the bundled messages. Note that, unlike the all data bundling option which bundles all data into one bundled message, the self data bundling option bundles only the data generated from the sensor node itself, which is the reason the term $\gamma_i e_i^f$ still remains. From the network-level perspective, the total energy consumption for message transmissions in the network could be described as follows:

$$\mathbf{E}^t = \sum_{i=0}^{N-1} e_i^t. \quad (4)$$

A. Maximization of Bundling Number for Energy Efficiency

With the model for energy consumption caused by message transmissions, we can increase the network energy efficiency by minimizing the total energy consumption for message transmissions (i.e., \mathbf{E}^t).

As shown in (3), a large number of bundled message transmissions (i.e., δ_i) could result in more energy consumption, but it could be decreased by bundling more messages in one transmission. Let Γ^i be the number of bundled messages at sensor node i . Then, a larger Γ^i could lead to a smaller δ_i , which could reduce total energy consumption for message transmissions. Consequently, we can minimize \mathbf{E}^t by maximizing Γ^i .

Even though we can increase the number of bundling for better energy efficiency, we cannot indefinitely because the E2E delay of the measurement data is sensitive to the number of bundling. Therefore, the maximization of bundling number for energy efficiency can be formulated as follows:

$$\begin{aligned} & \text{maximize } \Gamma \\ & \text{subject to } \chi^{\min} \leq \Gamma^i \leq \chi^{\max}, \forall i \in [0, \dots, N-1], \end{aligned} \quad (5)$$

where

$$\Gamma = \sum_{i=0}^{N-1} \Gamma^i.$$

Note that Γ is the total bundling number in the network and that χ^{\min} and χ^{\max} are the lower and upper bounds of the measurement bundling number which are application-specific parameters and could be specified by user.

B. Constraining E2E Delay

We define the E2E delay of sensor node i as the difference between the time of a certain measurement m at the sensor node and the time of the reception of the resulting message by the head:

$$\mathbf{D}_{e2e}^i \triangleq \sum_{l=0}^{L-1} D_l^i = T_m^{i,r} - T_m^{i,s}, \quad (6)$$

where D_l^i is the link delay at link l of L links from sensor node i to the head, $T_m^{i,r}$ and $T_m^{i,s}$ are the receiving time at the head and the measuring time at the sensor node respectively, the latter of which is a time with respect to the reference clock at the head translated by a time synchronization scheme. Specifically, the \mathbf{D}_{e2e}^i is a path-level delay which consists of several link-level delays in the network. Considering the bundling procedure, the link delay at link l for sensor node i could be described as follows:

$$D_l^i = D_{prop}^{i,l} + D_{serv}^{i,l} + D_{bund}^{i,l}, \quad (7)$$

where $D_{prop}^{i,l}$ denotes the propagation delay which is typically in nanosecond level in WSN, $D_{bund}^{i,l}$ is the delay caused by the bundling procedure which is in multiples of the measurement interval (e.g., 5×1 s for the measurement interval of 1 s and the bundling number of 5). Based on the service time model for TinyOS [10], we can model $D_{serv}^{i,l}$ as follow:

$$D_{serv}^{i,l} = \begin{cases} D_{SPI}^{i,l} + D_{succ}^{i,l} + (N_{try}^{i,l} - 1) \cdot D_{retry}^{i,l}, & N_{try}^{i,l} \leq N_{max}^{i,l} \\ D_{SPI}^{i,l} + D_{fail}^{i,l} + (N_{max}^{i,l} - 1) \cdot D_{retry}^{i,l}, & N_{try}^{i,l} > N_{max}^{i,l} \end{cases} \quad (8)$$

where

$$\begin{aligned} D_{succ}^{i,l} &= D_{MAC}^{i,l} + D_{frame}^{i,l} + D_{ACK}^{i,l}, \\ D_{fail}^{i,l} &= D_{MAC}^{i,l} + D_{frame}^{i,l} + D_{waitACK}^{i,l}, \\ D_{retry}^{i,l} &= T_{retry}^{i,l} + D_{frame}^{i,l} + D_{waitACK}^{i,l}. \end{aligned}$$

Note that, the delay parameters—i.e., one-time serial-peripheral interface (SPI) bus loading delay $D_{spi}^{i,l}$, medium access control (MAC) layer delay $D_{MAC}^{i,l}$, frame transmission

delay $D_{frame}^{i,l}$, acknowledgment (ACK) transmission delay $D_{ACK}^{i,l}$ and ACK waiting delay $D_{waitACK}^{i,l}$ —in the above equations are platform-dependent values, and their values are typically in the order of milliseconds. In addition, $N_{try}^{i,l}$ and $N_{max}^{i,l}$ are the current and the maximum allowed number of transmissions for a successful delivery, and $T_{retry}^{i,l}$ is the user-defined backup time of retransmission. For simplicity and energy efficiency, the packet retransmission is not taken into account in our proposed scheme since there are usually not many packet retransmissions in the network with lower traffic. So (8) could be simplified as follows:

$$D_{serv}^{i,l} = D_{SPI}^{i,l} + D_{MAC}^{i,l} + D_{frame}^{i,l} + D_{ACK}^{i,l} \quad (9)$$

where the value of $D_{serv}^{i,l}$ is around 10ms based on the reference values in [10].

The link delay in (7) could be further simplified when the measurement interval for an application ($\mathbf{I}_{meas}^{i,l}$) is much larger than the service delay ($D_{serv}^{i,l}$): Because $D_{bund}^{i,l} > \mathbf{I}_{meas}^{i,l}$, $\mathbf{I}_{meas}^{i,l} \gg D_{serv}^{i,l}$ also implies $D_{bund}^{i,l} \gg D_{serv}^{i,l}$. Hence

$$D_{link}^{i,l} \approx D_{bund}^{i,l} \quad \text{if } \mathbf{I}_{meas}^{i,l} \gg D_{serv}^{i,l}. \quad (10)$$

Note that the service delay $D_{serv}^{i,l}$ should not be ignored in case the application requires frequent measurements, i.e., $\mathbf{I}_{meas}^{i,l}$ is comparable to $D_{serv}^{i,l}$.

In typical hierarchical multi-hop WSNs, sensor nodes located in different layers handle different amount of traffic: For instance, the gateway node in the upper layer has to handle the message traffic from its offspring sensor nodes as well as itself; the higher layer it is located in, the more message traffic it has to handle. This means that even two sensor nodes with the same bundling number (i.e., Γ^i) could have different bundling delays due to the variance in their message traffics. By introducing a message traffic coefficient ($\frac{1}{1+\lambda^i}$) for each sensor node that periodically measures data with the same measurement interval (i.e., $\mathbf{I}_{meas}^{i,l}$), the bundling delay at sensor node i (D_{bund}^i) could be represented as follows:

$$D_{bund}^i = \frac{\Gamma^i}{1 + \lambda^i} \cdot \mathbf{I}_{meas}^i, \quad (11)$$

where λ^i denotes the number of offspring sensor nodes. Then the D_{e2e}^i for the applications with normal measurement interval could be modeled as follows:

$$\mathbf{D}_{e2e}^i = \sum_{l=0}^{L-1} D_{bund}^i. \quad (12)$$

With (12), we can also constrain the E2E delay in the optimal bundling problem in (5) with the user-defined E2E delay requirement (\mathbf{D}_{e2e}^{max}): For $i \in [0, 1, \dots, N-1]$,

$$\mathbf{D}_{e2e}^i \leq \mathbf{D}_{e2e}^{max}. \quad (13)$$

C. Constraining Synchronization Accuracy

Since the proposed optimal message bundling approach is based on the reverse asymmetric time synchronization scheme, the synchronization accuracy depends on the report interval

of the synchronization messages which, in turn, are carried by the bundled messages. In such a case, the user-required synchronization accuracy (\mathbf{SA}^{min}) could be maintained through constraining the E2E delay of the bundled message when sensor nodes generate measurement data periodically. Based on the empirical sets—i.e., \mathcal{T} —of the relationships between synchronization accuracy and SI previously provided in Section II, the user-required synchronization accuracy could be translated to the delay requirement as follows:

$$\mathbf{D}_{e2e}^{SA} = \mathcal{T}(\mathbf{SA}^{min}). \quad (14)$$

Combining (12) and (14), the synchronization accuracy could be achieved through constraining the E2E delay as follows: For $i \in [0, 1, \dots, N-1]$,

$$\mathbf{D}_{e2e}^i \leq \mathbf{D}_{e2e}^{SA}. \quad (15)$$

D. ILP model

Combining the objective function (5) and the two constraint sets (13) and (15), we can formulate the optimal bundling problem as the following ILP:

$$\begin{aligned} & \text{maximize } \Gamma = \sum_{i=0}^{N-1} \Gamma^i \\ & \text{subject to} \\ & \chi^{min} \leq \Gamma^i \leq \chi^{max}, \quad \forall i \in [0, \dots, N-1], \\ & \mathbf{D}_{e2e}^i \leq \min(\mathbf{D}_{e2e}^{max}, \mathcal{T}(\mathbf{SA}^{min})), \quad \forall i \in [0, \dots, N-1], \end{aligned} \quad (16)$$

where the E2E delays of all sensor nodes are jointly constrained by the user-defined E2E delay \mathbf{D}_{e2e}^{max} and the synchronization accuracy \mathbf{SA}^{min} requirements, and the bundling number of each sensor node is constrained by the user-defined lower χ^{min} and upper χ^{max} bounds, respectively. Applying the set of optimal bundling numbers computed from this ILP model to the sensor nodes, the required E2E delay and synchronization accuracy could be jointly maintained while the bundled message transmissions are still minimized.

IV. SYSTEM DESIGN

Fig. 3 shows a system architecture for the proposed optimal bundling based on the ILP model formulated in Section III-D, where the two subsystems—i.e., the *performance maintainer* at the head and the *parameter adapter* at each sensor node—are built to achieve the optimization target.

A. Performance Maintainer at Head

Since the time synchronization operation is centralized at the head in EE-ASCFR and AHTS, we first build the reference time synchronization system at the head as a component of the proposed system. The time synchronization is achieved through the *MAC-layer Time Recorder* and the *Time Synchronization Maintainer*, the latter of which translates timestamps between the head and a sensor node. With the time synchronization component, a measurement timestamp recorded at the sensor node—i.e., T_m^s in Fig. 1—is translated into a

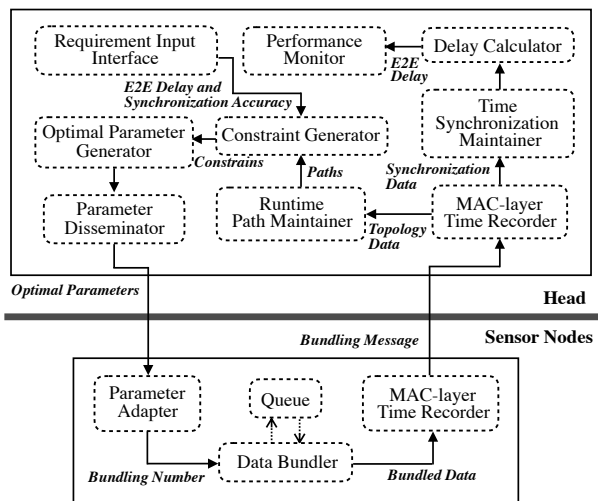


Fig. 3. System architecture of the proposed optimal bundling.

timestamp based on the hardware clock of the head. Then, the E2E delay is obtained as a difference between the translated measurement timestamp and the receiving timestamp of T_m^r through the *Delay Calculator*. Afterwards, the runtime E2E delay is monitored through the *Performance Monitor*.

Based on the topology data carried in each bundled message, the routing paths for all sensor nodes are recovered in the *Runtime Path Maintainer*, and one set of paths is generated and delivered to the *Constraint Generator*. The user-defined requirements of E2E delay and synchronization accuracy are captured through the user interface of *Requirement Input Interface*. By combining the performance requirements and the current path information, the *Constraint Generator* generates a set of constraints and passes it to the *Optimal Parameter Generator*, where the optimal bundling number for each sensor node is obtained as a solution of the ILP model. Finally, the optimal bundling numbers from the *Optimal Parameter Generator* are delivered to sensor nodes by the *Parameter Disseminator*.

B. Parameter Adapter at Sensor Nodes

To reduce the computational complexity required by the proposed optimal bundling on the sensor nodes, three lightweight components (including the *MAC-layer Time Recorder* from the time synchronization scheme) are implemented at sensor nodes. The *Parameter Adapter* receives the optimal bundling number and delivers it to the *Data Bundler* which bundles that number of measurement data temporarily stored in the *Queue* plus timestamps into one message. Then the bundled message will be again timestamped for T_3 by the *MAC-layer Time Recorder* as shown in Fig. 1.

V. EXPERIMENTAL EVALUATION

The proposed approach is implemented on a real three-hop WSN testbed consisting of five TelosB [11] sensor

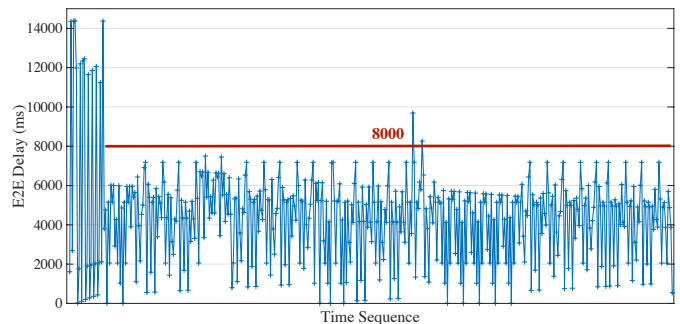


Fig. 4. E2E delay performance of the optimal bundling under static E2E delay requirement setting and the maximum bundling number of 15.

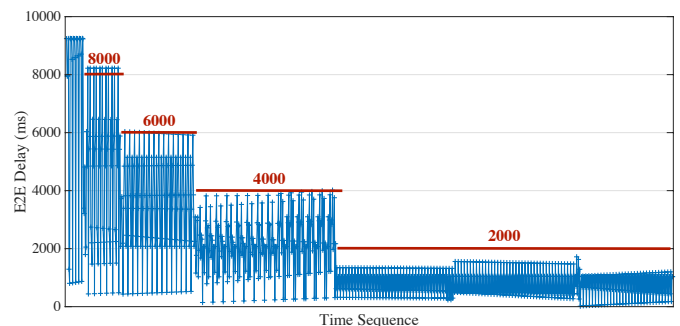


Fig. 5. E2E delay performance of the optimal bundling under dynamic E2E delay requirement setting and the maximum bundling number of 10.

nodes (i.e., head (#0)↔gateway (#1)↔gateway (#2)↔leaf (#4) and head (#0)↔gateway (#1)↔leaf (#3)). During the experiments, each sensor node generates one measurement per second, and the E2E delays of the latest measurements in bundled messages from all sensor nodes are collected and stored in a time sequence in order of their arrivals at the head, which are shown in Fig. 4 and Fig. 5. The red horizontal lines with numbers (in milliseconds) indicate the E2E delay requirements for corresponding time periods, and the requirement of synchronization accuracy is set to $5\mu\text{s}$ for all experiments.

A. Delay Performance Under Static Requirement Setting

We first evaluate the E2E delay performance of the optimal bundling under static requirement setting and the maximum bundling number of 15. We run the experiment for 3600 s to demonstrate the *long-term maintenance capability*.

As shown in the Fig. 4, the E2E delays can exceed 14 s before the optimal bundling is applied. Once the optimal bundling is applied with the requirement of 8 s, however, we can see that the E2E delay is controlled and kept under the requirement for most of the time. Note that there are few data points crossed the requirement line; because the gateway node serves its own measurement data first, the data from its offspring nodes, sometimes, could be buffered in the queue and sent by the next available message, which would increase the E2E delay of the corresponding message.

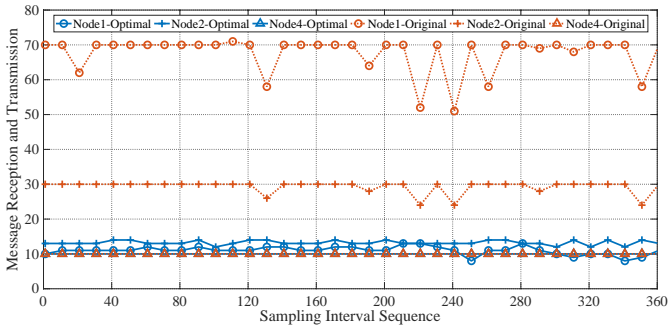


Fig. 6. Number of message receptions and transmissions of sensor nodes with and without optimal message bundling for 3600 s with sampling interval of 10 s.

B. Delay Performance Under Dynamic Requirement Setting

We also evaluate the E2E delay performance of the optimal bundling under dynamic requirement setting with the maximum bundling number of 10 to demonstrate its *run-time maintenance capability*. During the evaluation, the E2E delay requirement is dynamically changed from 8 s to 2 s step-by-step as shown in Fig. 5.

The results demonstrate that the proposed optimal bundling nicely handles multiple requirements of E2E delay throughout the experiment. As discussed in Section V-A, however, some data points slightly cross the requirement line of 8 s, which is due to the neglect of the service time (i.e., $D_{serv}^{i,l}$ in equation (7)). When the optimal bundling numbers are too strict which just fulfills the requirement, the influence of the neglect of the small service time would be notable.

C. Synchronization Accuracy and Energy Efficiency

With the novel time synchronization schemes of EE-ASCFR and AHTS, the synchronization accuracy could be fulfilled as far as the E2E delay of the bundled message satisfies the synchronization interval: The synchronization interval—i.e., E2E delay—exhibited in the evaluation results as shown in Fig. 4 and Fig. 5, could overfulfill the SI requirement (e.g., 10 s SI could lead to 2.34 μ s synchronization accuracy as illustrated in Table. I), which proves that the synchronization accuracy could be strictly followed.

To evaluate the energy efficiency, we indirectly estimate it by comparing the number of message receptions and transmissions with and without optimal bundling. Taking the path of $0 \leftrightarrow 1 \leftrightarrow 2 \leftrightarrow 4$ as an example, the number of message receptions and transmissions of the sensor nodes 1, 2, 4 in the experiment of static E2E delay requirement setting in Section V-A is illustrated in Fig. 6. The number of message receptions and transmissions of each sensor node is counted every 10 s over the period of 3600 s. With the proposed optimal bundling, all the sensor nodes could maintain their message receptions and transmissions around the number of 10. Without the optimal bundling, on the other hand, the numbers of their message receptions and transmissions are relatively larger,

whose average of 35 is over triple of that with the optimal bundling.

VI. CONCLUDING REMARKS

We have proposed an approach to optimize the number of bundled messages at sensor nodes in a WSN under the constraints of time synchronization accuracy and E2E delay. To solve the optimal bundling problem, we formulate it as an ILP model and employ the novel asymmetric time synchronization scheme. To the best of the authors' knowledge, this is the first work to optimize message bundling for energy consumption under the joint constraints of synchronization accuracy and E2E delay in the context of WSNs. The practical evaluation results on a real testbed demonstrate the long-term and runtime maintenance capability of the proposed approach.

Note that bundling a larger number of messages results in a longer payload, which may lead to possible link degradation such as the packet reception ratio degradation. In this regard, link quality requirements could be introduced to the optimization model as additional constraints to take into account more impacts on the overall performance by the bundling procedure.

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