An Inter-networking Mechanism Using Stepwise Synchronization for Wireless Sensor Networks

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Abstract. To realize the ambient information society, multiple wireless networks deployed in the region or carried by users are required to cooperate with each other. Since duty cycles and operational frequencies are different among networks, we need a mechanism to allow networks to efficiently exchange messages. In this paper, we propose a novel inter-networking mechanism where two networks are synchronized with each other in a moderate manner, which we call stepwise synchronization. With our proposal, nodes near the border of networks adjust their operational frequencies in a stepwise fashion to bridge the gap between intrinsic operational frequencies. For this purpose, we adopt the pulse-coupled oscillator model as a fundamental theory of synchronization. Through simulation experiments, we show that the communication delay and the energy consumption of border nodes are reduced, which enables wireless sensor networks to communicate longer with each other.

Keywords: Wireless Sensor Network, Synchronization, Pulse-Coupled Oscillator Model.

1 Introduction

The ambient information society is the concept and framework where intelligent environment detects, reasons, and satisfies overt and potential demands of people without their interaction [1,2,3]. In the ambient information society, people do not need to be aware of existence of networked information devices embedded in the environment. They do not need to intentionally access a network to control the environment to make it comfortable and satisfy their demands. Instead, the embedded network controls the environment and provides personalized information services to a user taking into account time, place, occasion, and person.

To realize the ambient information society, networks deployed and operating in the same environment must cooperate with each other in exchanging information, sharing information, and controlling each other. For example, a person has a wireless body area network which consists of vital sensors, accelerometers, PDA, and other devices. On the other hand, a room has embedded wired and wireless networks which consist of sensors and actuators for environmental control for example. Intelligent home appliances also constitute embedded networks. When the person enters the room, those networks

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should cooperate with each other for smart environmental control. However, in general, those devices organize different and independent networks operating on different control policies, e.g. operational frequency. Therefore, so that the room provides the person with a comfortable environment, we need a mechanism for different networks to smoothly and dynamically connect and share their information. However, it is not a trivial task.

There are several proposals on dynamic composition of multiple networks [4,5]. In [4], they consider a mechanism for overlay networks to dynamically compose a hierarchical structure by two types of composition schemes, i.e. absorption and gatewaying. In [5], cooperation between wireless networks is accomplished by organizing an overlay network by connecting gateway nodes belonging to different wireless networks. Although they can be applied to ambient information networking to some extent, they have a major problem that they do not take into account the difference in operational policies, more specifically, operational frequencies of different wireless sensor networks.

In general, wireless sensor networks adopt a sleep scheduling or duty cycling mechanism to save energy. Operational frequencies, that is, frequencies that they wake up and resume operation, are different among networks depending on application's requirement and characteristics of devices. For example, an air conditioner would obtain and use the temperature information every minute to adjust its thermostat. On the other hand, devices to detect locations of people have to report their detection result very frequently at an order of seconds. When they want to exchange information among them for intelligent control of room temperature to intensively regulate the temperature around a person in the room, a node belonging to the location detection system has to stay active in order to wait for a node belonging to the thermal management system to wake up in transmitting a message. Even when an energy-efficient MAC protocol such as S-MAC [6] and X-MAC [7] is used, such communication consumes the substantial energy at the former node and it would bring danger of energy depletion.

Our research group considers stepwise synchronization between wireless sensor networks for smooth and moderate inter-networking. In [8], the concept of stepwise synchronization is introduced, where sensor nodes located near the border of two networks adjust their operational frequencies to bridge the gap in their intrinsic operational frequencies. Since only nodes near the border change their operational frequency, the remaining nodes can keep their frequency and thus energy consumption in inter-networking can be reduced. The stepwise synchronization is self-organized based on a nonlinear mathematical model of synchronization of oscillators, called the pulse-coupled oscillator (PCO) model [9]. The PCO model describes emergence of synchronization in a group oscillators with different frequencies through mutual interactions through stimuli. By adopting the PCO model to scheduling, operational frequencies of nodes can be appropriately adjusted without any centralized control in wireless sensor networks. However, in [8], only an idea of stepwise synchronization is shown and no detailed description on mechanisms is given.

Therefore, in this paper, we propose a realistic mechanism of stepwise synchronization for inter-networking among wireless sensor networks with different operational frequencies. In our mechanism, we strengthen the degree of entrainment at border nodes to intensively shift the operational frequency toward that of the other network while the degree of entrainment is weakened as the distance to the border increase. As a result, the operational frequencies of nodes near the border are adjusted to somewhere between the original operational frequencies of wireless sensor networks. Through simulation experiments, we verify the practicality of our proposal in comparison with the case where each of networks keeps its intrinsic operational frequency.

The rest of this paper is organized as follow. First in section 2, we explain the pulse-coupled oscillator model. Next in section 3, we describe the details of our proposal. In section 4, we show and discuss results of our simulation experiments. Finally, we conclude the paper in section 5.

2 Pulse-Coupled Oscillator Model and Synchronization

A pulse-coupled oscillator model is a mathematical model which explains synchronized flashing of a group of fireflies [9]. It is considered that a firefly maintains a biological timer, based on which it intermittently flashes. The flashing frequency depends on its intrinsic timer frequency, which could be different among individuals. However, when fireflies form a group, they begin to flash in synchrony. A mechanism of biological synchronization is explained as follow. When a firefly observes a flash of another firefly, it is stimulated and its timer advances by a small amount. Because of nonlinearity in timer or stimulus, by repeatedly stimulating each other, their timers begin to expire synchronously, then flash at the same time. Among PCO models [9,10,11], in this paper we use the model proposed in [9].

In the PCO model [9], oscillator i maintains phase ϕ_i $(0 \leq \phi_i \leq 1)$ of a timer and state x_i $(0 \leq x_i \leq 1)$ given by a function of phase. The dynamics of phase ϕ_i is determined by the following differential equation.

$$\frac{d\phi_i}{dt} = F_i \tag{1}$$

where F_i stands for the intrinsic timer frequency of oscillator i. State x_i is determined from phase ϕ_i by the following monotonically increasing nonlinear function,

$$x_i = \frac{1}{b} \ln[1 + (e^b - 1)\phi_i] \tag{2}$$

where b $(0 < b)$ is a dissipation parameter that dominates the rate of synchronization.

When phase ϕ_i and state x_i reach 1, oscillator i fires and both phase ϕ_i and state x_i go back to 0. When an oscillator fires, the oscillator stimulates oscillators that are coupled with the firing oscillator. If oscillator j is stimulated by oscillator i at time t, oscillator j increases its state x_j by a small amount ϵ and phase ϕ_j changes accordingly as

$$x_j(t^+) = B(x_j(t) + \epsilon), \tag{3}$$

where

$$B(x) = \begin{cases} x & (0 \leq x \leq 1) \\ 0 & (x < 0) \\ 1 & (x > 1) \end{cases}$$

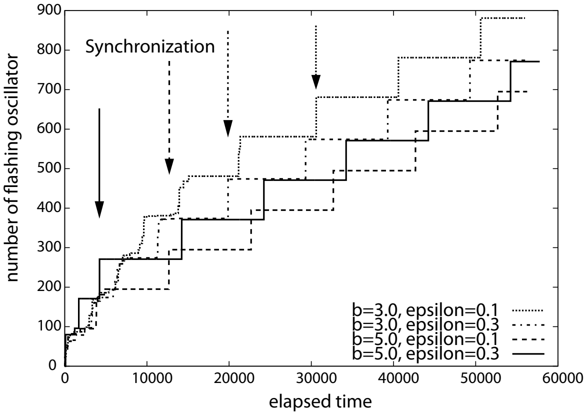

Fig. 1. Cumulative number of flashing oscillators

and

$$\phi_j(t^+) = \frac{e^{bx_j(t^+)} - 1}{e^b - 1} \tag{4}$$

When state $x_j(t^+)$ and phase $\phi_j(t^+)$ reach 1 by being stimulated, oscillator j also fires. At this time, oscillators i and j are considered synchronized. To avoid overshoot and instability, an oscillator is not stimulated by two or more oscillators at the same time, and an oscillator is not stimulated at the time when it fires.

In Fig. 1, we show how the cumulative number of flashing oscillators changes with different parameters b and ϵ against time. 100 nodes are arranged in a 10×10 grid. Each node is coupled with neighboring nodes in up, right, down, and left directions. The operational frequency of nodes is identical among nodes and their initial phase is set at random. The height of stepwise increase in the number corresponds to the number of oscillators simultaneously flashing. As indicated by arrows, the time when a group of oscillators reach synchronization and begins to flash in synchrony is about 30,000 with "b=0.1, ϵ=3.0", about 20,000 with "b=3.0, ϵ=3.0", about 13,000 with "b=1.0, ϵ=5.0", and about 4,000 with "b=0.3, ϵ=5.0", respectively. When we adopt larger b and ϵ, the speed of synchronization apparently increases. Although delay is not taken into account in drawing the figure, it is known that the synchronization is accomplished in the environment with loss and delay of stimuli [12,13].

3 Inter-networking Mechanism Using Stepwise Synchronization

In applying the PCO model to synchronization, a wireless sensor node corresponds to an oscillator. It stimulates neighbor nodes in the range of radio signals by broadcasting a message. A message is used for both of synchronization and data communication with such a mechanism where control messages for synchronization are embedded in messages for sensor data [14].

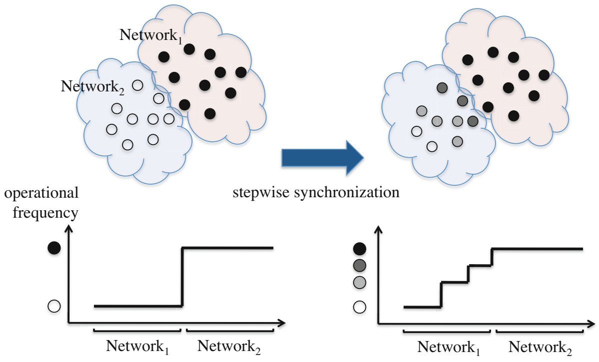

Fig. 2. Stepwise synchronization

Node i maintains state x_i and phase ϕ_i as variables of a timer of frequency F_i and calculates its new state and phase at regular intervals, e.g. at the granularity of timer. When state x_i and phase ϕ_i reach 1, node i sets both state x_i and phase ϕ_i at 0 and tries to broadcast a message which informs neighbor nodes that the node fires. Since a wireless channel is the shared medium, there is possibility that broadcasting is delayed to wait for the channel to become available. However, from our previous experiments, the influence of delay on synchronization is negligible [12]. When a node receives a broadcast message, it is stimulated. The stimulated node, say node j, increments its state x_j by a small amount ϵ by Eq. (3) and calculates new phase ϕ_j^+ based on the new state x_j^+ by using Eq. (4). If the new state x_j^+ and new phase ϕ_j^+ reach 1, node j also fires and broadcasts a message. Since duty cycling is adopted on a node, only neighboring nodes that are awake can receive stimuli. Details of integration of duty cycling and the PCO model will be given later.

Now we propose a stepwise synchronization-based inter-networking mechanism. In our mechanism, we assume that two or more wireless sensor networks operating in different operational frequencies, at which nodes wake up and resume operation by duty cycling, co-exist and nodes originally belonging to the same network are synchronized to the same frequency by a PCO-based synchronization mechanism. A node can communicate with any nodes in its communication range independently of whether they belong to the same network or not, as far as they are awake and ready to communicate. A node can know the distance, i.e. the number of hops, from the border of networks by using a mechanism which will be given later.

As an example, in Fig. 2, two wireless sensor networks with different operational frequencies are adjacent, and they attempt to cooperate. When we couple border nodes to let them stimulate each other, two wireless sensor networks will be unified to a single network with the operational frequency identical to the faster one. If the difference in the operational frequency is too large, they will remain independent. Therefore, we need a new mechanism to accomplish stepwise synchronization where only a part of network is involved in the synchronization and those networks with largely different operational frequencies can be synchronized. For this purpose, we adjust the degree of entrainment in accordance with the distance to the border. We focus on the fact that the dissipation b

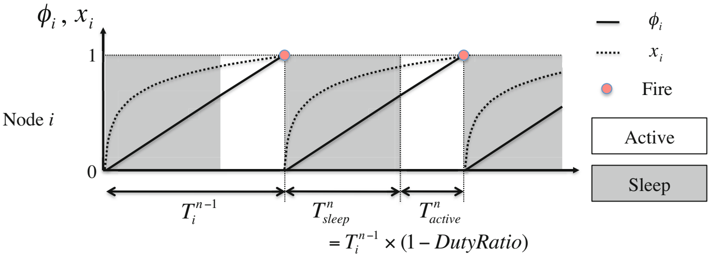

Fig. 3. Duty cycling

and the stimulus ϵ influence the degree of entrainment and the speed of synchronization (see Fig. 1).

In our proposal, we set larger values of b and ϵ, e.g. $b = 4.0$ and $\epsilon = 0.3$, at nodes located at the border of wireless sensor networks to strengthen entrainment and shift the operational frequency much. By receiving stimuli from the other network, nodes located at the border of wireless sensor networks actively changes their operational frequencies for larger parameters. Then smaller values are applied to nodes as the distance to the border becomes larger, e.g. $b = 3.5$ and $\epsilon = 0.1$. Nodes distant from the border of wireless sensor networks are also entrained by receiving stimuli from nodes located at the border, but the impact is smaller for smaller parameters and thus their operational frequencies stay rather closer to the original frequency. Consequently, we observe a stepwise change in operational frequencies around the border of two networks as illustrated in Fig. 2. Such stepwise synchronization can bridge the large gap in operational frequencies which cannot be overcome by the PCO model alone.

Now, we describe details of our proposal. Figure 3 shows the duty cycling in our proposal. Node i maintains state x_i and phase ϕ_i of a timer of frequency F_i. The phase automatically advances and the state accordingly changes independently of whether it is awake or sleeping. When state x_i and phase ϕ_i reach 1, node i sets both state x_i and phase ϕ_i at 0 and tries to broadcast a stimulus message. After the duration required to broadcast a stimulus message, node i goes to sleep for $T_{sleep}^n = T_i^{n-1} \times (1 - DutyRatio)$ independently whether it could successfully broadcast a stimulus message or not. T_i^{n-1}, called operational interval, is defined as the duration from the $n - 1$-th firing timing to the n-th firing timing and $DutyRatio$ is the duty ratio parameter which is determined in advance. Although a sleeping node does not receive any stimulus message, there is a case that the state and phase occasionally reach 1. In such a case, a node wakes up to broadcast a stimulus message and after broadcasting it immediately resumes the sleep state for the remainder of T_{sleep}^n. When T_{sleep}^n has passed, the node wakes up and becomes capable of sending and receiving messages for the duration of $T_{active}^n = T_i^{n-1} \times DutyRatio$. When node i receives a stimulus message in its active period, it calculates its new state and phase by Eqs. (3) and (4). If the new state and new phase reaches 1, node i fires, broadcasts a stimulus message, and goes to sleep.

So that other nodes in the network can recognize their relative distance to the border, all nodes at the border, which have received messages from the other network, sets the distance field in the header of stimulus message it broadcasts as 1, meaning that the message is from a node at the border. By receiving messages, a node can appropriately set its distance by adding 1 to the minimum value in the distance field of received messages. The distance information is also embedded in messages that it broadcasts, so that the distance information propagates through a network. Once a node recognizes its distance to the border, it adjusts b and ϵ in accordance with the distance. In this paper, the relationship between a pair of parameters b and ϵ and the distance is determined from preliminary experiments. A node at the border begins to use value 0 for the distance field, if it has not received any messages from the other network for a certain period of time to notify other nodes of the end of cooperation. Receiving this message, distance information is initialized to 0 on other nodes.

In addition to duty cycling based on the PCO-model, we further adopt duty cycling on the MAC layer. Low power listening (LPL) is an approach widely used in energy-efficient MAC protocols such as X-MAC [7]. With X-MAC, a node periodically wakes up by turning on a transceiver to see whether there is any message destined to itself. The duration that a node is ready for reception is denoted as R_l and the interval between successive active periods is denoted as R_s when the transceiver is off. A sender node that intends to send a message first transmits small messages, called Short Preamble, to notify a receiver of the existence of message. It keeps sending preambles until it receives an ACK for the preambles from an intended receiver. When a receiver, that is, a node that the sender wants to send the message to, wakes up, it would receive one of preambles during its active period. Then, the receiver sends back an ACK message to the sender and extends its active period accordingly. On receiving the ACK, the sender begins to send the message. After receiving the whole message, the receiver sends an ACK again to the sender. In a case of broadcasting, where a message is not intended for any specific node but all nodes in the vicinity, a sender begins to send a message itself repeatedly for the duration of slightly longer than R_s without communication initialization by Short Preamble. There is no acknowledgement either for broadcasting.

4 Performance Evaluation

4.1 Simulation Settings

We arranged 50 nodes in a 16×16 area as shown in Fig. 4. In Fig. 4, nodes in the upper-left area belong to Network 1 and the others do Network 2. Therefore, each of networks has four border nodes located in the overlapping area. A circle shown in Fig. 4 illustrates the communication range of the node centered at the circle and each node can communicate with nodes located within the communication range. Parameters are set as summarized in Table 1. In Table 1, S_{pre}, S_{ack}, S_{stim} and S_{data} stand for durations that a node sends a Short Preamble, an ACK, a stimulus message and a data packet, respectively. The operational interval between successive broadcasting is about 23 to 25 seconds in Network 1 and 130 to 143 seconds in Network 2. Initial states are set at random. Parameters b and ϵ used in cooperation are shown in Table 2 for each number of hop counts from the border. The duty ratio is set at 0.3 at all nodes.

In our simulation, the sink node of Network 1 sends a data message to the sink node of Network 2 by using multihop unicast communication once per 10 operational cycles. Data messages take the shortest path to the receiver node following the diagonal of the

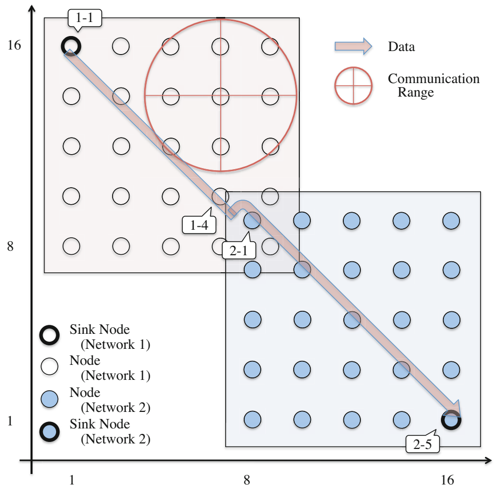

Fig. 4. Node layout in simulation

Table 1. Parameter settings

PCO		X-MAC			
param.	value	param.	value [ms]	param.	value [ms]
b	3.0	S_{pre}	2.0	R_s	200
ϵ	0.1	S_{ack}	2.0	R_l	20
f_1	0.040 - 0.044 [Hz]	S_{stim}	4.0		
f_2	0.007 - 0.0077 [Hz]	S_{data}	4.0		

networks. When a node between the sink nodes is active and receives a data message, it immediately tries sending the message to a next-hop node. It transmits preambles until it receives an ACK from the next-hop node, even after the end of the PCO-based active period, i.e. expiration of timer. When the transmission of the data message is completed, the node begins to sleep if the phase of timer is in the range of the PCO-based sleep period. Otherwise, it keeps awake in the PCO-based active period.

For the purpose of evaluation of energy consumption, we assume that each node is equipped with an Atmel ATmega 128L processor, a Texas Instruments CC2420 radio chip and two AA batteries. The details of energy consumption model is summarized in Table 3.

4.2 Results and Discussion

We compare two scenarios, where both networks keep their intrinsic frequencies denoted as “independent”, and our proposal is adopted denoted as “proposal”. As performance measures, we use communication delay which is defined as the duration between

Table 2. PCO parameters used in cooperation

param.	distance to border				
	border	1 hop	2 hop	3 hop	4 hop
b	4.0	3.5	3.0	2.0	1.5
ϵ	0.3	0.1	0.05	0.05	0.05

Table 3. Energy consumption model

param.	value
Initial energy	2000 [mAh]
Processor active current	8 [mA]
Sleeping current	15 [uA]
Sending current	9.9 [mA]
Waiting and receiveing current	19.7 [mA]

the time when a node begins to send preambles for transmission of a data message and the time when a node receives an ACK for message reception.

First, we confirm that the stepwise synchronization is accomplished. Figure 5 shows how nodes in Network 2 (slower network) adapt their operational frequencies. Each square corresponds to a node and the color shows resultant operational intervals. In this figure, we see that the operational interval of nodes at the border, i.e. four nodes located upper-left of the network, becomes about 50 [s], closer to the operational interval of Network 1. On the other hand, the operational interval of other nodes become longer than that of those border nodes as the distances to the border become larger. As a result, the stepwise change in operational frequency emerges in accordance with the distance to the border.

Next, we evaluate per-hop communication delay. Figure 6 shows the median of the communication delay of all data messages transmitted in the simulation runs. In Fig. 6, "1-1, 1-2" corresponds to the communication delay from Node(1-1) to Node(1-2), for example. Those nodes from Node(1-1) to Node(1-4) belong to Network 1 (faster network), and those from Node(2-1) to Node(2-5) belong to Network 2 (slower network). Node(1-4), Node(2-1) and Node(2-2) are nodes located at the border of networks. In Fig. 6, in the case of "independent", although all communication delays between nodes belonging to the same network are quite small, communication delay between nodes located at the border is 23 [s]. It is because Node(1-4) has to wait for Node(2-1) located at the border of Network 2 to wake up. On the other hand, in the case that our proposal is adopted, communication delays between nodes belonging to Network 2 become large. It is because that they do not wake up at the same time any more for different operational frequencies shown in Fig. 5. However, the communication delay between nodes located at the border of networks is reduced. The reason that the communication delay between Node(2-1) and Node(2-2) is small in both cases is that both Node(2-1) and Node(2-2) are located at the border and they are synchronized. As stated above, communication delay results from waiting intransmission, during which a node consumes energy. We next evaluateenergy consumption, which is a major concern of a wireless sensor network.

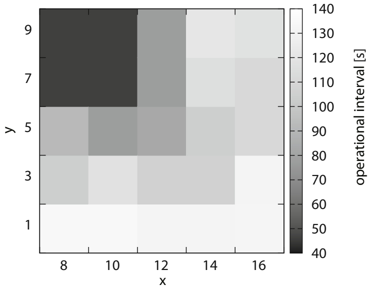

Fig. 5. Results: operational intervals in stepwise synchronization (Network2)

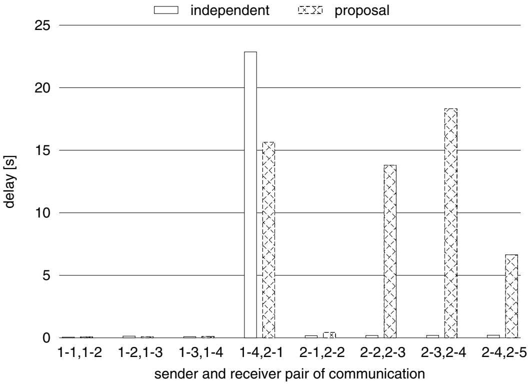

Fig. 6. Results: communication delay of each hop

Finally, simulation results of energy consumption are summarized in Fig. 7. In Fig. 7, in the case of "independent", although the energy consumption of nodes located inside of networks is almost constant, Node(1-4) located at the border of Network 1 consumes the largest energy among all nodes in waiting for Node(2-1) to wake up. On the other hand, in the case that our proposal is adopted, the amount of energy consumed at the border node, i.e. Node(1-4), is reduced from 10.3 [mAh] to 8.9 [mAh] at the sacrifice of increased energy consumption at nodes in Network 2.

Although the total amount of consumed energy is larger with our proposal than the case of independent networks, we consider that our proposal benefits wireless sensor networks in (i) it balances energy consumption among nodes, which leads to prolongation of the lifetime of border nodes, (ii) it can enable wireless sensor networks with largely different frequencies to synchronize with each other (not shown in this paper), and (iii) since the stepwise synchronization emerges as a consequence of mutual interaction between nodes and there is no deterministic rule to determine stepwise operational frequencies, it can adapt to various situations, e.g. increase in the number of networks to cooperate, cooperation among moving networks, and different degree of cooperation.

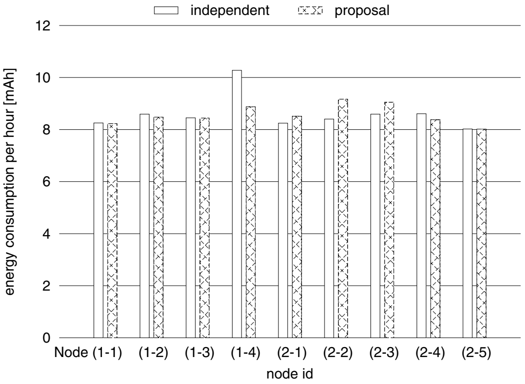

Fig. 7. Results: energy consumption per hour

5 Conclusion

In this paper, to achieve smooth and moderate inter-networking between wireless sensor networks with different operational frequencies, we propose a stepwise synchronization-based inter-networking mechanism. In this mechanism, we adopt the pulse-coupled oscillator model to autonomously accomplish stepwise synchronization. Through simulation experiments, it was shown that the delay in communication between border nodes and the energy consumption at the border nodes were reduced, but at the sacrifice of energy at nodes near the border in the slower network.

Since only preliminary and proof-of-concept evaluation is conducted in the paper, we further plan to comprehensively evaluate the proposal in such scenarios where the difference in operational frequencies is much larger between two networks, there are more than three networks to cooperate, and the degree of overlapping, i.e. the number of border nodes, dynamically changes.

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