Comparison of robustness of time synchronisation in sensor networks

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Abstract: In sensor networks, time synchronisation between sensor nodes is important because it affects not only the efficiency of information gathering but also the energy consumption. Since network sizes and sensor network environments change at varying rates, different time synchronisation strategies are required for different networks. The pulse-coupled oscillator model is self-organised synchronisation method which can be used to achieve local interaction between individuals for the synchronisation of entire networks. Centralised synchronisation methods also exist, such as the multi-hop reference broadcast synchronisation method which synchronises the entire network by transmitting the differences in the timers of reference nodes through networks divided into clusters. In this paper, we compare the influence of delay jitter and packet loss resulting from the lower layer protocols on these two techniques. We also investigate the energy consumption of both methods.

Keywords: sensor networks; synchronisations; PCO; pulse-coupled oscillators; CSMA/CA; carrier sense multiple access with collision avoidence, multi-hop RBS.

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1 Introduction

Continued improvement in wireless technology that provides low-cost, compact and reliable sensor devices is focusing research on sensor networks consisting of sensor nodes (Akyildiz et al., 2002). Sensor networks are suitable for various services, including environment monitoring, merchandise logistics management and military surveillance and they are growing in size and complexity as applicability spreads. While attracting such large expectation, many problems still lie in sensor networks. The sensor node may stop its operation unexpectedly since it is driven by a battery, a reliable communication cannot be always expected due to wireless connection, it is difficult to centrally control several hundreds or several thousands of sensor nodes which are deployed around large monitoring region. Considering these aspects of sensor networks, the capability to maintain the function of network under the topology changes or the undesirable circumstances is more required than improving the network performance or optimising the network efficiency. In this paper, we consider this capability as the robustness.

As a means to bring robustness, increasing importance is being placed on the control methods which are inspired by the phenomena found in nature. Biological systems constantly respond to environment changes, and adjust, control and adapt themselves based on information gained from communication with their local peers. Hence, self-organisation is achieved through this interaction with environment and communication. For instance, in the group that takes the collective action such as ant, bee, etc. simple behaviour of each individual leads to a intellectual activity with uniformity among the group. This feature of biological methods, 'self-organization', has a great importance. Self-organised structure has no component which controls the entire system, randomness and local interactions between the components to bring the robustness to the system (Leibnitz et al., 2007).

In a sensor network, the time synchronisation between sensor nodes is becoming an important feature. Additionally, energy consumption is a crucial problem for sensor networks, as each sensor node has only limited power resources of a low-capacity battery. Sleep control is one efficient power-saving technique, which when used, ensures that a sensor node wakes up only when it is required to work (Sivrikaya and Yener, 2004). In addition, data gathering becomes more efficient when the sensor nodes transmit information at coordinated times (Wakamiya and Murata, 2005). These power-saving techniques cannot be implemented without the synchronisation of all sensor nodes. Furthermore, since time information itself can be important for particular applications, time synchronisation is indispensable for acquiring time series data, such as temperature measurements, of the entire monitoring region.

Pulse-coupled oscillators (PCOs) are a self-organised time synchronisation control which synchronises the network with distributed behaviour. PCO is a model of biological systems, such as groups of fireflies or cardiac pacemaker cells. Each node is an oscillator that periodically emits a pulse to coupled oscillators and then adjusts its own phase based on the pulses it receives from them (Mirollo and Strogatz, 1990). The advantage of this control is the robustness brought about its behaviour where each node makes a decision based on only local information without any instructions from leaders. The synchronicity is achieved by a simple manner without depending on the initial state.

Reference broadcast synchronization (RBS) (Elson et al., 2002) has been proposed as a centralised time synchronisation technique. This technique realises an exact synchronisation not by absolute time but by relative time offsets. Therefore, the advantage of RBS is that it is not affected by the transmission time or the access time which occurs on the MAC layer. However, as RBS uses centralised control, so it is inapplicable if the network size becomes large. Multi-hop RBS is the technique to which RBS is improved for large-scale networks (Elson et al., 2002). In this technique, a network is divided into multiple clusters of size determined by the transmission range and then the head of each cluster becomes an RBS base node. Then, the entire network is synchronised through execution of RBS in each cluster and transmission of the synchronous time of a certain cluster using multi-hop communication. Thus, multi-hop RBS is a type of centralised control based on the information obtained for the whole network. Although, multi-hop RBS can achieve an accurate synchronisation, certain problems may arise when it is implemented in real sensor networks. In large-scale networks, it is difficult for the sink node, which orders each cluster head to perform RBS synchronisation within its cluster, to know the information of the entire network. When radio communication is unstable, the synchronous time might not be transmitted correctly and a incorrect reference time would be exchanged between the nodes in the same cluster.

However, some papers have elaborated on the efficiency and robustness of bio-inspired approaches such as clustering (Barbarossa and Scutari, 2007), the robustness in the field of time synchronisation has not cleared. Our interest lies in examining the trade-offs among bio-inspired, self-organising control methods and centralised methods in the field of time synchronisation control. Past research has evaluated the performance characteristics of PCO but has rarely compared it with other synchronisation control techniques (Hong and Scaglione, 2005; Bush, 2005; Tyrrell et al., 2006). In these papers, PCO is treated as a method of realising a very precise synchronisation in the order of microseconds. Those studies that evaluate PCO, do so only under ideal conditions and do not consider the influences of packet delays and losses that severely influence the precision in synchronisation and the time to synchronisation. Moreover, although the goal of those papers is to achieve a rapid time synchronisation based on the transmission of pulses instead of usual packets, it is unrealistic from an economic viewpoint to include a device which is capable of sending and receiving physical pulses additionally to the usual packet transmission. However, the synchronisation accuracy demanded on the application level is not so high in many cases. For this reason, we study the performance of PCO on packet level, which does not require a particular circuitry to transmit and receive physical pulses. Moreover, since packet loss and delay jitter resulting from the MAC layer also influences the packet layer, it is necessary to carry out evaluations taking these effects into consideration.

In this paper, we apply packet level PCO that works as overlay of the packet transmission based on IEEE 802.15.4 (IEEE, 2003) for applications that do not need high-accuracy and high-speed synchronisation. We also consider the effects of the lower layers in the comparative evaluations of PCO and multi-hop RBS. Carrier sense multiple access with collision avoidance (CSMA/CA) is used as the standard MAC layer transmission protocol in IEEE 802.15.4 for sensor networks. We implemented PCO and multi-hop RBS as synchronisation mechanisms above CSMA/CA, compared PCO and multi-hop RBS using simulations and investigated the network environment for which each method is most suited.

The organisation of this paper is as follows. We first explain the network models and define synchronisation in Section 2. In Section 3, we describe synchronisation with PCO and we show how multi-hop RBS operates in Section 4. In Section 5, we present the results of our simulations and conclude by discussing plans for future work in Section 6.

2 System definition

We will explain how sensor node behave, definition of synchronisation and what kind of delays are focused in this paper.

2.1 Network model

We assume that sensor nodes have the ability to communicate constantly and are not able to change a communication range according to the situation. All the sensor nodes have the same capabilities and have an oscillator indicating its internal time. It is assumed that the cycle of all oscillators is the same. Internal time of oscillator $C_i(t)$ is expressed as Equation (1) using clock drift $a_i(t)$, offset $b_i(t)$ and clock cycle T_i of node i. In this paper, we assume that none of sensor nodes is synchronised at the initial state and the offset is set at random.

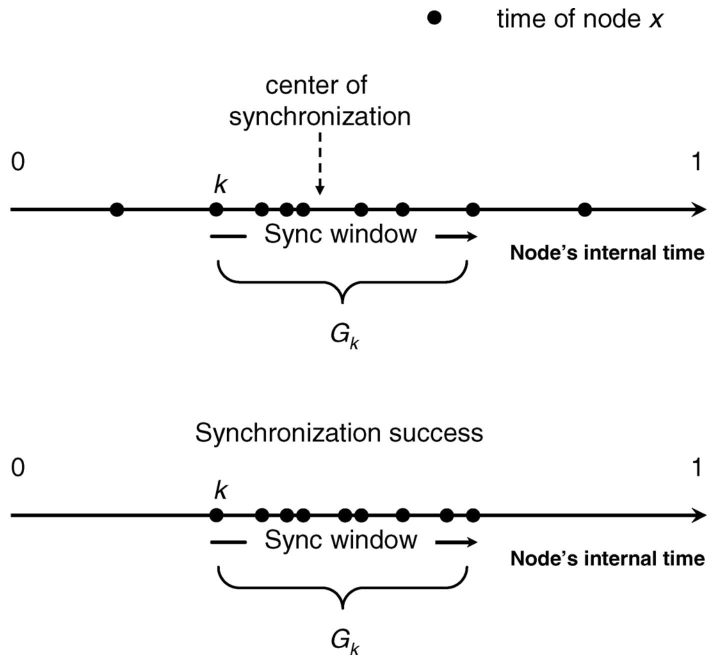
$$C_i(t) = a_i(t)\,T_i + b_i(t) \tag{1}$$

Sensor nodes use CSMA/CA as their MAC layer protocol. With CSMA/CA, carrier sensing is done before the packet is transmitted and it is checked channel is free. We adopt the CSMA/CA protocol according to protocol description of IEEE 802.15.4.

2.2 Synchronisation model

In real networks, it is difficult for all nodes to completely synchronise due to transmission delay, interference and packet loss. In addition, the required precision of the synchronisation may differ according to the application. Therefore, we use a synchronisation window W as the parameter to determine synchronisation and use this as an index of target synchronous accuracy (Werner-Allen et al., 2005).

Figure 1 A synchronisation window is used to determine if the nodes are synchronised



Consider the relative offset $z_{ij} \in [-0.5, 0.5]$ between nodes n_i and n_j, which have the internal time $b_i, b_j \in [0, 1]$. z_{ij} is expressed as

$$z_{ij} = ((b_j - b_i + 1.5) \bmod 1.0) - 0.5 \tag{2}$$

We define the synchronisation group $G_i(w)$ which starts from node n_i over a synchronisation window w which decides the size of group as follows:

$$G_i(w) = \left\{n_j \,|\, 0 < z_{ij} < w\right\} \tag{3}$$

Then, we find the largest group.

$$S_i = |G_i(w)| \tag{4}$$

$$S_k = \max_{\forall i} S_i \tag{5}$$

where S_i is the number of nodes in group $G_i(w)$ and S_k is the largest group size. If S_k is equivalent to the number of all sensor nodes, the group G_k is in the complete synchronous state as shown in Figure 1. The average internal time over all sensor nodes in group G_k becomes the centre (reference point) of synchronisation.

2.3 Delay model

The most serious problem for networks that require precise synchronisation is the latency between the time when a node tries to transmit a packet and the time another node receives it. Therefore, the degree to which latency can be eliminated is an important issue. In this paper, we consider two types of delay: access delay and propagation delay.

- *Access delay:* this is the time needed to confirm whether the channel is free and is influenced by the MAC layer and CSMA/CA. Access delay becomes exponentially longer as the channel becomes more crowded.
- *Propagation delay:* this is the period between the time a packet is transmitted and the time it reaches its destination. This value is d/c, where d is the distance between source and destination and c is the speed of light. Propagation delay is much shorter than access delay.

3 Bio-inspired time synchronisation control

The distributed communication strategy that we propose is based on the packets instead of pulses. This condition makes synchronisation difficult but it is necessary to control the real network. PCOs provide a model which shows the behaviour of two connected nodes. In the following, we will describe PCO as a self-organised method for time synchronisation control in sensor networks.

3.1 Mirollo and strogatz model

The M&S model (Mirollo and Strogatz, 1990) is a time synchronisation mechanism for applying PCO to sensor networks. An oscillator has a phase $\phi \in [0, 1]$ representing the internal time and a state $x \in [0, 1]$ representing the phase.

Let us consider the set $O = \{O_1, \ldots, O_N\}$ of N oscillators. Each oscillator has phase ϕ_i and state x_i, which is given by the function f_i and changes overtime.

$$x_i = f_i(\phi_i) \tag{6}$$

In particular, $f_i(0) = 0$, $f_i(1) = 1$ and phase ϕ_i changes from 0 to 1 every clock cycle T_i and $\mathrm{d}\phi_i/\mathrm{d}t = 1/T_i$. When its phase reaches 1, the oscillator fires and the phase is reset to 0. In this paper, we use following function as f_i (Mirollo and Strogatz, 1990).

$$\forall i,\ f_i(\phi_i) = \frac{1}{b} \ln\left[1 + \left(e^b - 1\right)\phi_i\right] \tag{7}$$

If the strength of the state function b is larger, the synchronisation time becomes smaller. If oscillator τ_i receives a pulse, then its oscillator increases its own state by ε and the two oscillators, O_i and O_j, are coupled.

$$x_j\left(\tau_i^+\right) = \begin{cases} x_j\left(\tau_i\right) + \varepsilon, & \text{if } x_j\left(\tau_i\right) + \varepsilon < 1 \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

By giving such a stimulus to each other, coupled oscillators become synchronised overtime.

3.2 Effect of delay on PCO synchronisation

The M&S model considers that the effect of the firing of a neighbouring node instantaneously takes place, regardless of delay. In fact, since there is time after a sensor node fires until transmits information, it is necessary for a node to take account of the delay while it is synchronising. In other words, the phase has to be changed so that it may precede from the delays. For that purpose, the receiving sensor node has to know-how much delay there was in the packet arrival.

In the reach-back firefly algorithm (RFA) (Werner-Allen et al., 2005), the timestamp is used to indicate the access delay on MAC layer. First, the sensor node stores the time of firing and transmits its data after a waiting period when it is confirmed by CSMA/CA that the channel is free. Thus, the receiving node can find out the delay after the source node fires by marking data packets using delay as the time stamp.

Although access delay can be indicated with a time stamp, it is insufficient for the M&S model to ignore the effects of delay, since the phase cannot be changed simultaneously with firing. Additionally, when the phase is changed at the same time as the effect of the firing is experienced, some problems arise. To avoid these problems, even if a sensor node receives information about a firing, the amount of the change in the phase should be stacked at once without being changed. Then, the value of the stack is announced and, the phase is changed after self-firing and waiting fixed time W. W should be longer than the back-off time of CSMA/CA.

4 Centralised time synchronisation control

4.1 Reference broadcast synchronisation

RBS (Elson et al., 2002) is a time synchronisation mechanism that does not require a time stamp. RBS does not set the time of the particular node but sets the times of neighbouring nodes. First, a reference packet, which does not contain a time stamp, is transmitted from a sensor node called a base node. A sensor node that receives this reference packet uses the packet arrival time as reference time for comparison with neighbouring sensor nodes. This method can be summarised as follows.

Step 1— A base node broadcasts a reference packet to neighbouring N sensor nodes.

Step 2— sensor nodes n_i which receive this reference packet store their own reception time T_i.

Step 3— A receiving node exchanges its reception time with other sensor nodes that receive the same reference packet.

Step 4— A receiving node n_i calculates the average time of error offset[i] of the exchanged reception time and its own reception time.

The offset[i] is given by Equation (9).

$$\text{offset}[i] = \frac{1}{N} \sum_{k=1}^{n} \left(T_i - T_k\right) \quad \forall_{i=1}^{N} \tag{9}$$

The main benefit of RBS is that it achieves a high accuracy in synchronisation which is not affected by access delay. The error in the reference time between the nodes that receive the same reference packet is caused by propagation delay, which is much smaller than access delay. Thus, access delay can be eliminated.

4.2 Multi-hop RBS

RBS can be effective only when all sensor nodes are arranged within the communication range of a base node. In other words, RBS cannot synchronise large-scale networks because nodes may be located outside the communication range of the base node. Therefore, the whole network is divided into clusters and RBS is applied to each cluster. A sensor node called a gateway node, which belongs to two or more clusters, translates the relative time between clusters. The mechanism for transmitting synchronous time information to the whole network is called multi-hop RBS.

In multi-hop RBS, the sensor node called the sink plays a key role in controlling the synchronisation of the whole network. First, the sink transmits the schedule for executing RBS to a cluster head by multi-hop communication. A cluster head that receives the schedule information carries out RBS within its own cluster and when it is confirmed that all the sensor nodes in the cluster can be synchronised, the cluster head tells the sink that RBS was completed. After the sink confirms that RBS has been carried out by all the clusters, it broadcasts the synchronisation time information in its own cluster to set the time of the entire network at the synchronous time of its own cluster. The gateway node that receives synchronous time information spreads it to the next cluster while it calculates the error in the synchronous time between clusters and notifies other sensor nodes in its same cluster. In this way, time synchronous information spreads throughout the network and all sensor nodes become synchronised.

5 Simulation results

In this paper, two versions of the simulation program that operate at higher layer above CSMA/CA were formulated, one with PCO and one with multi-hop RBS. The performance of these two versions will be now evaluated and compared. The observation area in which sensor nodes are deployed is circular. The parameters that were used in the simulations are shown in Table 1. The firing cycle T is 0.16 sec, which is 10,000 symbols where the symbol is back-off base duration on CSMA/CA. The maximum simulation time is assumed to be 100 sec. We use various metrics to evaluate the simulation results: the ratio of synchronised nodes, the probability of synchronisation, the time to synchronisation and the clock variance.

In the PCO program, contrary stimuli can be given mutually and a completely synchronous state can collapse because the network that had reached a synchronous state was unstable. Therefore, we consider a network as synchronised when a network remains for five consecutive cycles in a completely synchronous state. We consider a network as synchronised in the case of multi-hop RBS, cluster synchronous information spreads to all the clusters and the network is in a completely synchronous state. The time taken until then is assumed to be the time to synchronisation. Time to synchronisation is not counted in either PCO or multi-hop RBS when the network does not meet these synchronous requirement. Similarly, the synchronous accuracy is measured by the variance of the phase of the sensor node. The smaller the variance becomes the more precise the time synchronisation is.

$$v = \frac{1}{N}\sum_{i=1}^{n} e_i^2 \tag{10}$$

$$e_i = \begin{cases} \bar{x} - x_i, & |\bar{x} - x_i| < 0.5 \\ 1 - |\bar{x} - x_i|, & \text{otherwise} \end{cases} \tag{11}$$

Table 1 Default parameter settings

Parameter	*Value*
Number of sensor nodes	200
Radius of monitoring region	100 m
Communication range	50 m
Packet loss rate	0.001
Synchronous window size	0.1
Stimulation of fire ε (PCO)	0.0008
Strength of state function b (PCO)	5
Firing cycle T (PCO)	0.16 sec
Maximum simulation time (PCO)	100 sec

where N is the number of nodes, x_i is the phase of sensor node i, $\bar{x}$ is the phase average of the largest group and e_i is the error between x_i and $\bar{x}$. Reliability of data was verified by using 95% confidence intervals from 400 trials.

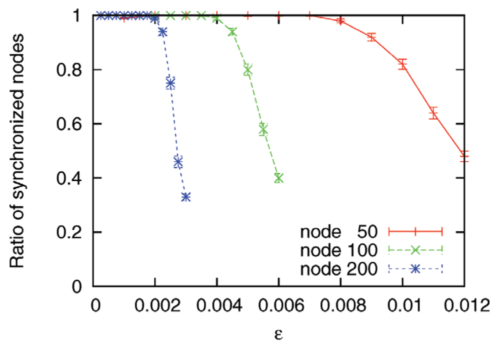
5.1 PCO control parameter: ε

There is a stimulation value ε as a control parameter that affects PCO synchronisation. PCO cannot achieve synchronisation if ε is not appropriately set. Figure 2 shows the results from simulations when the value of ε is changed with the number of sensor nodes. At a small ε value, however, the possibility that many sensor nodes will synchronise increases because the sensor nodes gradually stimulate each other and approach a synchronous state. It takes a long time for the network to synchronise when the connectivity between sensor nodes is low. With a large ε value, in contrast, the probability of synchronisation decreases dramatically because the sensor node receives too many stimulations and the network cannot converge to a stable state. As a result, there is an optimal value of ε from the two viewpoints of probability of synchronisation and time to synchronisation. Although the factor that determines the optimal value of ε is the number of connected sensor nodes, it seems that both the total number of sensor nodes and the size of the monitoring region is closely correlated with this value. It is also necessary to take into consideration the fluctuation of connectivity among sensor nodes and network topology if sensor nodes are not uniformly deployed. Thus, finding an optimal ε value is not a simple problem and is left to future work.

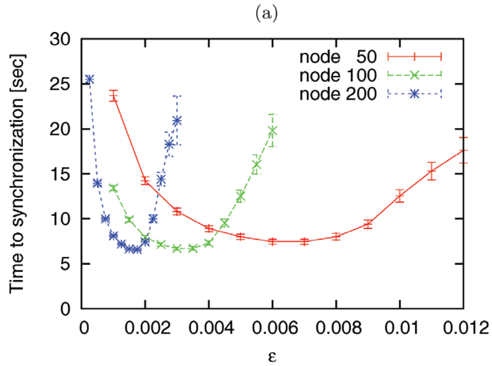
5.2 Network scalability

In sensor networks, lots of devices can be deployed over a wide area, so it is important for synchronous technique to be able to synchronise networks of various size. Figure 3 shows how the size of the network affects each synchronisation mechanism. Figure 3(b) and (c) shows that multi-hop RBS establishes precise synchronisation in a short time in high-node density environments. However, multi-hop RBS loses a significant number of synchronized nodes as the density of sensor nodes decreases (Figures 3(a)). By contrast, PCO shows stable performance in point of ratio of synchronised nodes. This is because of the lack of connectivity of multi-hop RBS compared with PCO. It is necessary for RBS to communicate, using communication range d between the sensor nodes on different edges

Figure 2 ε affects the performance of PCO: (a) value of ε suitable for synchronisation and (b) optimal value of ε for synchronisation (see online version for colours)



(a)



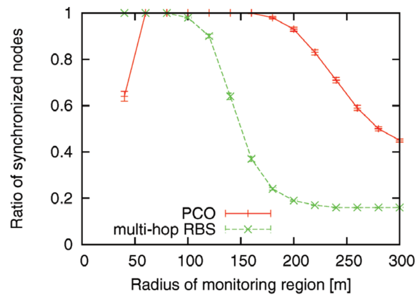
(b)

of a cluster and the radius of a cluster is limited to $d/2$. Thus, PCO and multi-hop RBS show relative performance advantages over each other based on network environment and which technique is used should be decided based on the application and the size of the monitoring region in which it will be used.

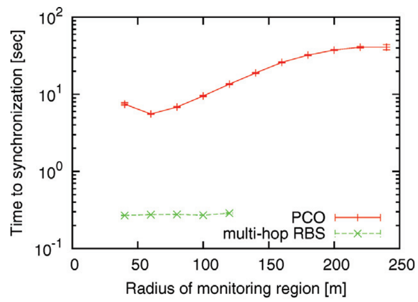
5.3 Robustness to packet loss

Synchronous techniques must be robust to packet loss because the radio technology used in a sensor network is fragile and the packets do not always reach the receiver. Figure 4 shows the effects of packet loss on the two synchronous methods. As shown in Section 5.2, PCO and multi-hop RBS demonstrate the relative performance advantages over each other depending on the environment. Figure 4(a) shows that almost all sensor nodes can be synchronised by both synchronous techniques even in unstable environments where packet loss occurs frequently. This is because PCO compensates for the effects of packet loss by causing sensor nodes to give repeated mutual stimulation and multi-hop RBS retransmits the packet if the ACK packet is not returned. However, in multi-hop RBS, almost all sensor nodes can be synchronised, but it is difficult for all sensor nodes to carry out a complete time synchronisation since the synchronous error produced by the packet loss within the cluster increases by a synchronous time spreading through clusters by multi-hop communications (Figure 4(b)). This affects the accuracy of synchronisation, as shown in Figure 4(c). For these reasons, PCO is effective in an environment where communication is unstable and a complete time synchronisation is necessary.

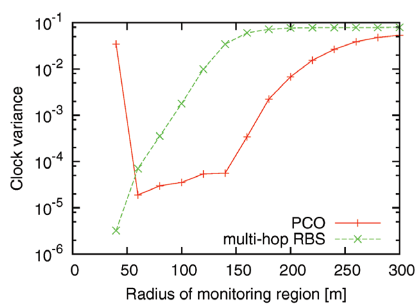
Figure 3 The evaluation over the size of the monitoring region: (a) PCO can synchronise all sensor nodes in a much wider monitoring region than multi-hop RBS. PCO is not available with very high-node density (where radius of monitoring region is 40 m); (b) multi-hop RBS is not able to synchronise a network where the radius of the monitoring region is larger than 110 m and (c) multi-hop RBS can accurately synchronise a network in a small monitoring region (see online version for colours)



(a)



(b)

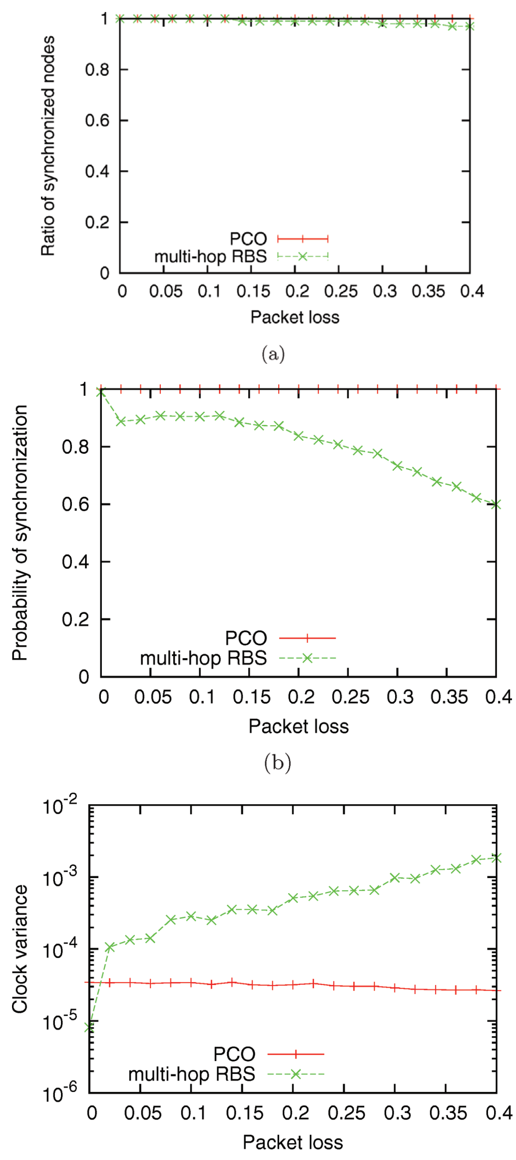


(c)

5.4 Energy consumption

It is an important problem to save energy in a sensor networks. Then, we confirmed what tendency was seen in energy consumption when the transmit range of a sensor node was changed. First, ratio of synchronised nodes is shown in Figure 5. As presented in Section 5.2, a suitable condition for synchronisation is different in PCO and multi-hop RBS. Since it is a target of synchronisation that all the sensor nodes synchronise, we clarify the tendency of energy consumption under the conditions that all sensor nodes synchronise (transmit range 30–120 m in PCO and 60–160 m in multi-hop RBS). Results are shown in Figure 6.

Figure 4 Packet loss performance; (a) both techniques show an extremely high value for the ratio of synchronised nodes; (b) only a few sensor nodes are out of synchronisation in multi-hop RBS due to expanding of the error caused by the packet loss and (c) PCO shows stable clock variance value regardless of packet loss (see online version for colours)



(c)

Figure 5 Effective transmit range is different between PCO and multi-hop RBS (see online version for colours)

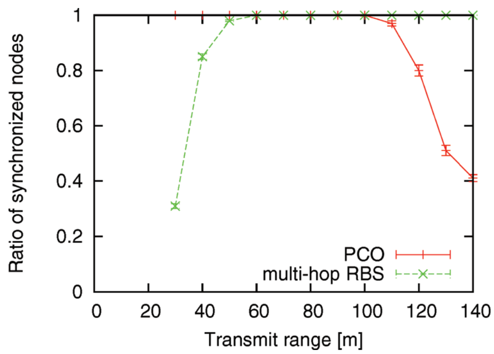
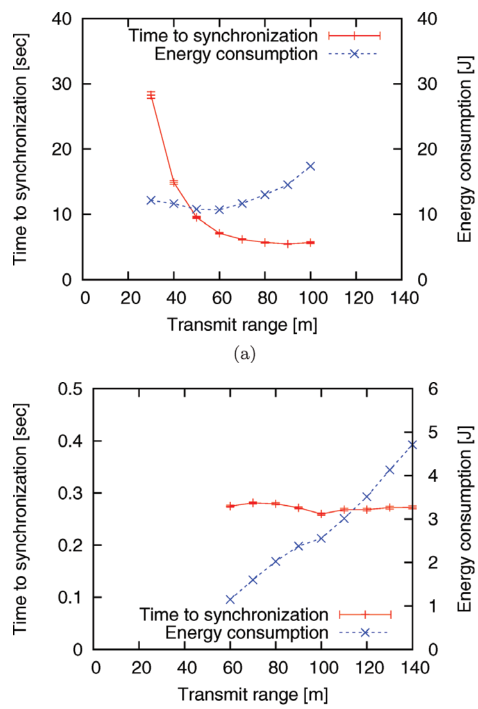


Figure 6 Relation between time and energy consumption necessary for time synchronisation: (a) PCO and (b) multi-hop RBS (see online version for colours)



(a)

(b)

Because the sensor node transmits a packet at constant intervals in PCO, the time to synchronisation has a direct influence on energy consumption. From Figure 6(a), sensor nodes receive more stimulation so that transmit range becomes large and time to synchronisation becomes short. However, energy consumption is proportional to the square of transmit range, too large transmit range is not optimal and energy consumption does not serve as the minimum when synchronising by the shortest time.

On the other hand, multi-hop RBS has much small energy consumption compared with PCO. This is caused by the difference of time to synchronisation. In multi-hop RBS, since the number of the packet which a sensor node transmits is almost fixed, energy consumption also increases simply as the transmit range increases. To save energy, it is preferable to set a minimum transmit range in which synchronisation can be achieved.

6 Conclusion

We comparatively evaluated two time synchronisation techniques, PCO and multi-hop RBS, from the viewpoint of scalability, robustness to packet loss and energy consumption in consideration of delay by CSMA/CA. We found that, bio-inspired time synchronisation control with PCO can achieve very stable time synchronisation regardless of the radio quality over a wide observation area. We also found that centralised time synchronisation control (multi-hop RBS) can establish highly precise and energy efficient time synchronisation in a short time at high node densities and in high-radio quality environments. Considering the characteristics of sensor networks, bio-inspired time synchronisation control is suitable to realise stable and assured synchronisation even if basic performance is inferior to centralised control. We leave to future work the discussion of the stability of the synchronisation in PCO. That is the investigation of ε value according to topology. Moreover, it is important to investigate the more suitable clustering technique for multi-hop RBS.

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