Isochronous MAC using Long-Wave Standard Time Code for Wireless Sensor Networks

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Abstract— **This paper proposes Isochronous-MAC (I-MAC), which utilizes low-frequency radio waves time synchronization for sensor networks. Using I-MAC, based on the Low Power Listening (LPL), all sensor nodes wake and listen channel periodically and synchronously. Since a sender can easily predict wakeup time of an intended receiver, it can shorten the length of preamble to make the receiver prepare for reception of the following data packet. This saves power consumption for the sender to rendezvous with the receiver. In the paper, we use an analytical model to investigate the impact of the data transmission frequency, the number of neighboring nodes, the wakeup period, the clock drift, and the time-synchronization frequency on the power consumption for consideration of the power overhead to perform the time synchronization. Those results demonstrate that I-MAC allows determination of any arbitrary wakeup period without much difficulty, whereas LPL requires a much more careful setting of the wakeup period because its optimum wakeup period is sensitive to the frequency of data transmission as well as to the number of neighboring nodes. Therefore, I-MAC has a great potential to reduce the power consumption in most situations compared with LPL, in spite of the overhead to perform time synchronization.**

Keywords-Sensor networks; Media access control; Low power listening; Time synchronization; Low-frequency radio wave

I. INTRODUCTION

A wireless sensor network comprises multiple small wireless sensor nodes, each of which is driven by a limited battery capacity. Each sensor node can obtain the necessary environmental information and send it through the multi-hop network to the base station, where it collects all data. Because of this available capability, it is useful for various applications. However, as the number of sensor nodes increases to several hundred or to several thousand, for example, the persistent necessity of changing batteries would be a considerable burden. For that reason, it is highly desirable to reduce the power being used by each sensor node, thereby increasing the total available time for the entire sensor network system.

Of the power consumed by all sensor nodes, the greatest fraction is the power used for wireless communications. For that reason, we must confront the issue of development of a new MAC that has much lower power consumption. An effective means to lower the power consumption in a MAC is to reduce the energy that is used during idle listening, in which the receiver must be activated, even when no packet is received. To do that, a type of MAC named Cycled Receiver MAC, which includes S-MAC [1], Low Power Listening (LPL) [2] and WiseMAC [3], has been developed. Using Cycled Receiver MAC, each node enters a receiving mode only during a specific wakeup duration time that occurs in every wakeup period. Reducing the duty cycle ratio, i.e., the ratio of wakeup duration to wakeup period, is one way for a cycled receiver MAC to reduce the power, i.e., it reduces the power used for idle listening.

In general, with a cycled receiver MAC, the longer the wakeup period, the longer the delay time in connection establishment. Therefore, under the condition of the same duty cycle ratio, the shorter the MAC wakeup period, the more advantageous it can be in terms of the delayed time.

The wakeup duration time of S-MAC is normally set as 115 ms. For LPL or WiseMAC, on the other hand, it is less than 50μs, which is sufficient duration to monitor the channel usage. Consequently, given the same duty cycle ratio, the wakeup period of S-MAC is larger; it is less advantageous than the other two methods because of its longer delay time. Comparing situations with the same delay time until the communication session is set up between the sending node and the receiving node, LPL is more advantageous than SMAC in terms of power consumption because LPL can have a smaller duty cycle ratio than S-MAC.

With LPL, the length of a preamble is set to the wakeup period. Consequently, the longer wakeup period causes the more power consumption of preamble transmission; that requirement conflicts with our goal to reduce the power consumption that is attributable to idle listening. The optimum wakeup period, as we will show later in this paper, is dependent on the transmission frequency and the number of neighboring nodes to which the data are sent. Overall, it is not easy to determine an optimum wakeup period for the entire network.

Another method, WiseMAC, is an updated version of LPL. Using WiseMAC, a receiving node makes its corresponding transmitter learn its future wakeup schedule by including the next wakeup timing in the ACK data. Therefore the transmitting node can shorten the preamble length for the next

transmission to the receiver based on the knowledge of the schedule. Clock drift in a node, however, increases the inaccuracy of this learning mechanism gradually with time. Therefore, this learning process of the wakeup schedule would not work as efficiently as expected unless some frequent communications have been established. To our knowledge, only the effect of the downlink from an access point to a sensor node seems to have been examined with WiseMAC. It has not been well evaluated in multi-hop communications.

In this paper, we propose Isochronous-MAC (I-MAC), which can synchronize the wakeup duration time at every node. This synchronization can be made using low-frequency radio waves. Currently, low-frequency radio waves service is available in America, Europe and Japan. One-chip LSI for Japanese service has been developed for small watches (ML6191-A03; OKI [7]); its required power consumption for time synchronization is as little as 90μW. Using I-MAC, since the synchronized wakeup time of every node can be known easily in advance, the preamble length can be shortened. The preamble length of I-MAC fundamentally depends on the number of time synchronizations to make and the clock drift of the crystal oscillator. Therefore, using I-MAC, when we try to determine the optimal wakeup period to reduce the overall power consumption, we can reduce the dependency of the transmission frequency and the number of neighboring nodes to which the data are sent. The preamble length with LPL and WiseMAC lengthens proportionally as the clock drift increases. With I-MAC, each node can correct the clock drift easily using the regularly performed time synchronization with the external signal. For this reason, I-MAC can determine the preamble length, assuming that it is used with a smaller clock drift than either LPL or WiseMAC.

Now we will describe the structure of this paper. In Section II, we will describe related works associated with the time synchronization in sensor networks. In Section III, we will describe our basic analysis on a cycled receiver MAC. Section IV will describe I-MAC in general. Section V will describe its mathematical modeling for the evaluation. Section VI presents the numerical results we obtained. Finally, we present our conclusions in Section VII.

II. RELATED WORKS ON TIME SYNCHRONIZATION

Various means of time synchronization for a sensor network have been researched. They are classified into two ways: "packet exchanging" and "external signal."

As packet exchanging techniques, Reference Broadcast Synchronization (RBS) [4], Timing-sync Protocol for Sensor Networks (TPSN) [5] and Flooding Time Synchronization Protocol (FTSP) [6] have been proposed. In addition, S-MAC also adopts a packet exchanging technique; S-MAC moderates the accuracy criteria for time synchronization through intentional setting of a longer wakeup time period.

With RBS, a reference node broadcasts a reference message. The receivers record their local time in receiving the reference message and exchange the recorded times with each other. RBS achieves the synchronization error of several microseconds.
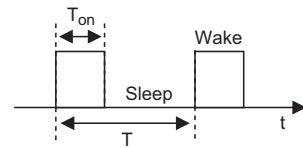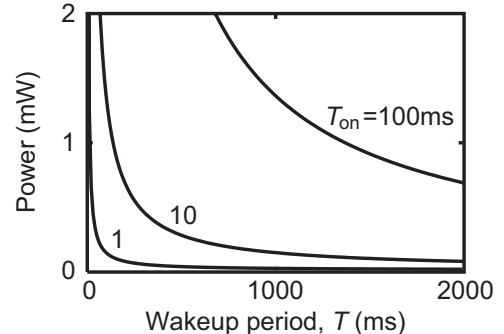

Figure 1. Periodic wakeup and sleep

Figure 2. Relation of T to the idle power (T_{on} = 1, 10 and 100 ms)

TPSN first creates a spanning tree of the network and then performs pair wise synchronization along the edges. Typically, TPSN has about twice the accuracy as RBS as far as the synchronization is concerned. It has achieved errors of less than 50μs between nodes that are separated by five hops.

Finally, FTSP creates multiple time stamps by broadcasting a synchronization packet regularly. Consequently, it obtains the clock drift at each node based on linear regression method. Correcting the clock drift, it can accomplish time synchronization with an error of 1μs.

In these time synchronization protocols, frequent packet exchanges to improve accuracy of time synchronization may cause more energy consumption overhead, and data packets and control packet for time synchronization may collide frequently if the data channel and control channel are the same.

One way to synchronize time using an external signal is to use GPS. The GPS allows synchronization of the time with accuracy of a few dozen nanoseconds. However, the GPS consumes much power. Even using a one-chip LSI (CXD2951; Sony [8]), 50 mW of power is consumed, which is too much consumption for time synchronization performed at a sensor node.

III. BASIC ANALYSIS FOR CYCLED RECEIVER MAC

This section describes characteristics of power consumption of a cycled receiver MAC without any transmission.

During the idle time, the cycled receiver MAC is activated during the wakeup duration time, T_{on}, which happens within every wakeup period of T. In other words, after the wakeup duration time is passed, it falls into sleep for the duration of $T - T_{on}$ (Fig. 1). The time length of T_{on} and the process made during that time length differ for every MAC. For example, S-MAC has a longer T_{on}; it is set with 115 ms.

With S-MAC, during that time, the sensor nodes exchange SYNC packet for the synchronization and RTS/CTS packets

for the connection establishment. On the other hand, another MAC, LPL, has a shorter T_{on}, less than 50μs, which is sufficient time to sense the channel status.

Fig. 2 shows the relationship of T_{on}, T and the idle time power consumption. To reduce the power consumption during the idle time using a cycled receiving MAC, longer T must be set. The relationship of T with the power consumption that is required during idle listening is inversely proportional. To the extent that T is longer, more delay would result. To reduce power consumption by adopting a shorter T, it is understood that the shorter T_{on} yields better results. As a result, LPL with a short T_{on} has excellent characteristics in terms of delay and power consumption reduction during the idle time. In this paper, we select use of the LPL as one MAC for comparison.

IV. GENERAL DESCRIPTION OF I-MAC

I-MAC, which we are proposing in this paper, enables all nodes to synchronize the time throughout a system, which resolves the problem that LPL poses. The method to synchronize the time is to use low-frequency radio waves as an external signal. Thereby, every node is synchronized.

A. Synchronization using Low-Frequency Radio Waves

Low-frequency radio waves that are used for time synchronization of watches are available in America, Europe and Japan. Time synchronization can be accomplished by receiving a time code which is broadcast from the base radio station using amplitude modulation (AM). Generally speaking, this way of time synchronization using low-frequency radio waves is available even inside of a building as long as the place is in an environment in which the AM waves can be received. Therefore, it is less restricted in terms of its usage environment than is GPS.

The time code includes the information of time from the second to the year level; it is sent at the rate of 1 bit/s using AM. One piece of time code information is sent in one minute. To ensure current time synchronization, a few pieces of time code information are received normally. As a result, one-time synchronization takes a few minutes. The time difference that results from this method using the base radio station is 1.5μs. For that purpose, one-chip LSI has been developed for watches aiming to achieve low power consumption with small size; the power consumption is as little as 90μW. Using low-frequency radio waves, current technology allows us to accomplish very accurate time-synchronization with low power consumption.

B. Isochronous-MAC

With I-MAC, all nodes of the entire network can wake up concurrently in the same period. When each wakes up, it senses the channel, which is the same action as that taken by LPL. If the channel is in an idle state during wakeup duration Ton, it reverts to a sleep state.

Fig. 3(b) shows the manner in which the packet is sent and received when our proposed MAC is used.

To send data, the sender first sends the preamble at the time to wake up the neighboring nodes. After that, it sends the data.

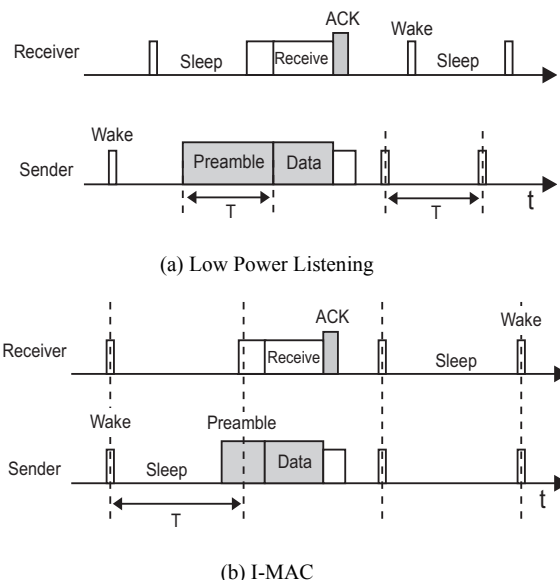

(a) Low Power Listening

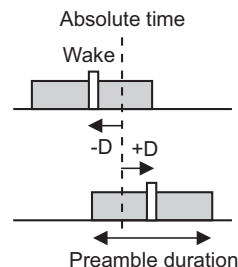(b) I-MAC

Figure 3.　Low Power Listening and I-MAC

Figure 4.　Maximum relative clock drift between nodes and preamble length

The receiver node returns the ACK data if the data are received correctly, and reverts to a sleep state. The preamble length must be sufficiently long for the other neighboring nodes, including the receiver node, to be able to be wake up. The timing by which each node wakes up might be shifted slightly because of the clock drift that each one has; the preamble length must be determined in light of this fact. The preamble length is determined based on the time-synchronization timing and the amount of the clock drift.

Now we assume ±D as the maximum clock drift of the crystal oscillator that might be shifted from the absolute time obtained using low-frequency radio-wave time synchronization. Thereby, the relative clock drift difference between any two nodes is ±2D maximum shifted from one of the nodes that is set as a base (Fig. 4). This fact tells that the total relative clock drift can fall in the width of 4D.

Two methods are available to shorten the I-MAC preamble length: more frequent synchronizations and less clock drift. More frequent time-synchronizations would also lessen the clock drift, which would help to reduce the necessary power consumption to send a preamble. However, it would increase the power consumption associated with time synchronization.

Incidentally, the LPL drift depends strongly on the accuracy of the crystal oscillator used. On the other hand, I-

MAC corrects the clock drift of the crystal oscillator at every time synchronization. For this type of correction, linear correction technique, which is used for FTSP, can also be used.

V. MODELING OF POWER CONSUMPTION

We will next use a model to identify, analytically, those parameters that would be associated most closely with the power consumption. To do so, the model is simplified: packet collisions are ignored.

The power consumption P_{total} to obtain for LPL and IMAC is definable with the active time period, T_{total}, and the total consumption energy, E_{total}, as expressed in the following equation.

$$P_{total} = \frac{E_{total}}{T_{total}} \qquad (1)$$

We will proceed with the modeling process separately for the energy consumption at sending and receiving times and at the idle time, as well as to obtain the E_{total} value.

First we will describe the consumption energy at the data sending and receiving times. Now we define N as the average number of nodes within the transmission range from any one node, and M as the average number of data transmissions made during the period of T_{total}. Because every node residing in the transmission area is expected to send data M-number of times, it is concluded that any one node is expected to receive data NM-number of times on average, during which time neither packet collisions nor retransmissions are presumed to be made. From the NM-number of data receptions, M-number of packet receipts are assumed to be made by the own node, and the other (N −1) M-number of times by other nodes. Here, we respectively define each pair of E_{send} and T_{send}, $E_{recv-own}$ and $T_{recv-own}$, and $E_{recv-other}$ and $T_{recv-other}$, as thee of data transmission, for one piece of data receiving by the own node, and for one piece of data receiving by other nodes. Using these variables, the energy E_{com} is consumed by data sending and receiving; the time T_{com} is required to accomplish that. The entire process happens during T_{total}. They are represented as the following equations.

$$E_{com} = ME_{send} + ME_{recv-own} + M(N-1)E_{recv-other} \qquad (2)$$

$$T_{com} = MT_{send} + MT_{recv-own} + M(N-1)T_{recv-other} \qquad (3)$$

The energy consumed to send and receive one piece of data and the necessary time for that are obtained next. Using S_{ack} as the ACK size, S_{data} as the data length, and R as the channel rate, we define T_{ack} as the time to send and receive an ACK, and T_{data} as the time to send and receive the data. We represent them in the form of

$$T_{data} = \frac{S_{data}}{R} \qquad (4)$$

$$T_{ack} = \frac{S_{ack}}{R} . \qquad (5)$$

Defining $T_{preamble}$ as the preamble transmission time, followed by P_{tx}, P_{rx}, and P_{sleep}, which respectively represent the power consumption at the times of transmission, receiving, and sleeping, E_{send} and T_{send} are given as

$$E_{send} = P_{tx}(T_{preamble} + T_{data}) + P_{rx}T_{ack} \qquad (6)$$

$$T_{send} = T_{preamble} + T_{data} + T_{ack} . \qquad (7)$$

The average time period spent for each node to start receiving data after it detects a preamble is $T_{preamble} / 2$. Therefore, $E_{recv-own}$ and $T_{recv-own}$ can be expressed as

$$E_{recv-own} = P_{rx}(\frac{T_{preamble}}{2} + T_{data}) + P_{tx}T_{ack} \qquad (8)$$

$$T_{recv-own} = \frac{T_{preamble}}{2} + T_{data} + T_{ack} . \qquad (9)$$

When receiving the data that are addressed to the other node, the node is assumed to enter into an idle state without sending an ACK. With this fact in mind, $E_{recv-other}$ and $T_{recv-other}$ are given as

$$E_{recv-other} = P_{rx}(\frac{T_{preamble}}{2} + T_{data}) \qquad (10)$$

$$T_{recv-other} = \frac{T_{preamble}}{2} + T_{data} . \qquad (11)$$

The energy consumption at an idle time is discussed next. With T given as a wakeup period, the energy E_T that is consumed during time T is provided as follows during the idle time.

$$E_T = P_{rx}T_{on} + P_{sleep}(T - T_{on}) \qquad (12)$$

Then the energy E_{idle} that is consumed at an idle time during T_{total} can be represented by the following equation.

$$E_{idle} = (\frac{T_{total} - T_{com}}{T})E_T \qquad (13)$$

Among the variables defined above, the only different one between LPL and I-MAC is the preamble transmission time $T_{preamble}$. The $T_{preamble}$ for LPL is T. In contrast, because I-MAC is dependent on the maximum clock drift D and the number of synchronizations C, it can be represented by the following equation, where F is the maximum error from the absolute time at the time synchronizations, and the clock drift varies linearly with time.

$$T_{preamble} = \frac{4D}{C} + T_{on} + 4F \qquad (14)$$

Each $T_{preamble}$ causes a change in E_{com} and E_{idle}. Therefore, we respectively define $E_{com-lpl}$ and $E_{com-imac}$ for the E_{com} of LPL and I-MAC, and respectively denote $E_{idle-lpl}$ and $E_{idle-imac}$ for their E_{idle}. With I-MAC used, the energy is consumed when the time is synchronized using low-frequency radio waves.

Defining P_{sync} as the power consumed during time synchronization, C as the number of synchronizations made during T_{total}, and T_{sync} as the time required for one synchronization, the energy E_{sync} that is consumed by the time synchronization made during T_{total} is $P_{sync}T_{sync}C$.

In conclusion, the total energy consumption $E_{total\text{-}lpl}$ of LPL, and $E_{total\text{-}imac}$ of I-MAC are given respectively as the following equations.

$$E_{total-lpl} = E_{com-lpl} + E_{idle-lpl} \qquad (15)$$

$$E_{total-imac} = E_{com-imac} + E_{idle-imac} + E_{sync} \qquad (16)$$

VI. NUMERICAL RESULTS

First we describe the parameters we use. The total activity period T_{total} is a whole day; M is therefore the number of transmissions made during a day, D is the maximum clock drift during a day without any time synchronization, and C is the number of synchronizations made during a day. The respective quantities of power consumed during TX, RX and SLEEP are $P_{tx} = 24.75$ mW, $P_{rx} = 13.5$ mW, and $P_{sleep} = 0.015$ mW. We used 19.2 kbps as the channel rate, which means that the listening time Ton for both LPL and I-MAC is $1/R$. S_{data} and S_{ack} are 64 Byte and 8 Byte. We defined the power consumed by the circuit that was used to synchronize the time using the low-frequency radio waves as $P_{sync} = 0.09$ mW, and the time spent to synchronize as $T_{sync} = 2$ min. Furthermore, the maximum error from absolute time F is 1.5μs.

Fig. 5 shows the relationship between the number of time synchronizations made during a day, C, and the time required to send a preamble, which is represented as $T_{preamble}$. The preamble length is understood to be inversely proportionate to the number of synchronizations, so that a preamble length can be made sufficiently small by having just about 50 times the number of synchronizations performed. In addition, it can be understood that a smaller clock drift will allow a shorter preamble.

Fig. 6 shows graphs representing the relationship of the total power consumption P_{total} against the number of neighboring nodes N to which transmissions are made when the number of transmissions M is taken as 100 times and the number of time synchronization C is 50. Looking at these graphs, we can understand that for both LPL and I-MAC, the power consumption is linearly proportionate to the number of neighboring nodes. For LPL, we understand that the slope of the lines varies according to the wakeup period T. For I-MAC, the slope of the lines stays the same. For this reason, with LPL, we must select the right wakeup period T for the right number of neighboring nodes N. If that choice were made mistakenly, the impact on power consumption would be considerable. Using I-MAC, on the other hand, we can understand that the longer wakeup period we choose, the more power consumption we can reduce. In other words, taking the number of neighboring nodes as fixed, we can understand that the power consumption level is not sensitive for every wakeup period, even if it is changed.

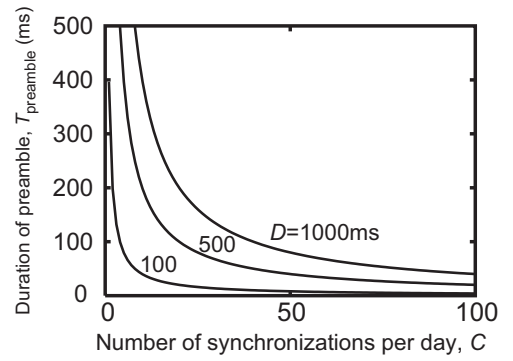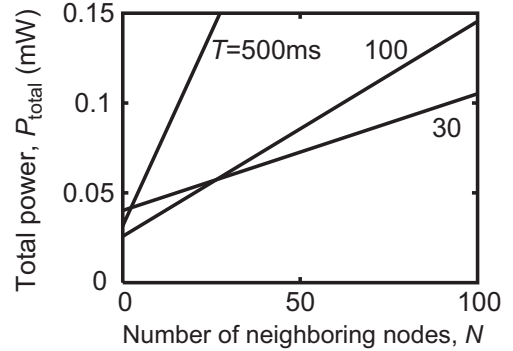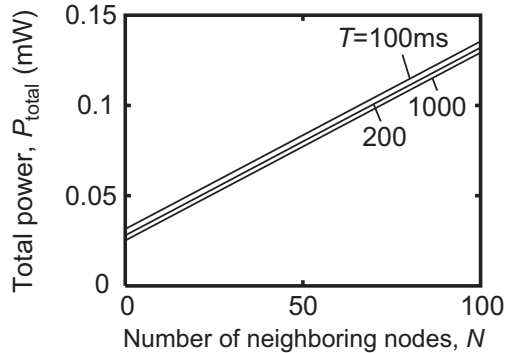Next we will specifically examine the sensitivity of the

Figure 5. Relation between duration of preamble transmission and the number of time synchronizations (D = 100, 500 and 1000 ms)


(a) Low Power Listening (T = 30, 100 and 500 ms)

(b) I-MAC (T = 100, 200 and 1000 ms)

Figure 6. Relation between the number of neighboring nodes and total power

total power consumption P_{total} against the number of transmissions M. Fig. 7 shows the relationship between the total power consumption and the wakeup period for both LPL and I-MAC, where the number of time synchronizations C is 50 and the number of neighboring nodes N is 10. Fig. 7(a) depicts the case in which the average number of transmissions a day, M, is 100, and Fig. 7(b) 1,000. For LPL, there exists an optimum wakeup period that consumes the least power for every number of transmissions M. For LPL, as mentioned previously, one must select the right wakeup period for the right number of transmissions. If that choice were mistakenly made, the impact given to the power consumption would be great.
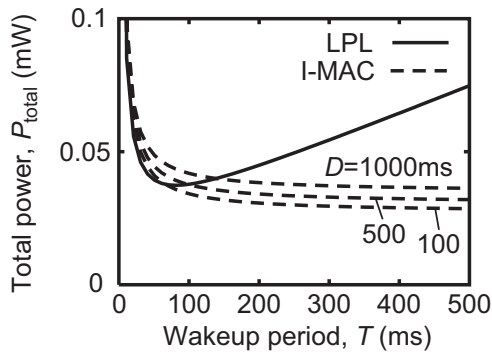
(a) $M = 100$ ($D = 100$, 500 and 1000 ms)
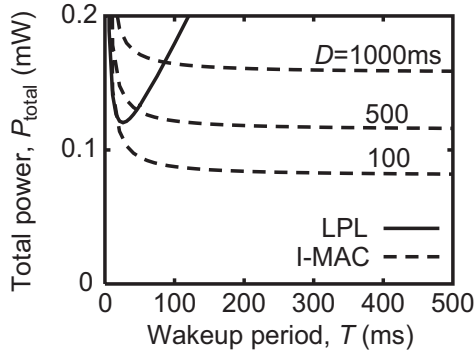
(b) $M = 1000$ ($D = 100$, 500 and 1000 ms)

Figure 7.   Relation between wakeup period and total power

For example, with an LPL, when $M = 100$, the wakeup period T that would consume the most appropriate power is 81.13 ms, and when $M = 1,000$, it is 25.61 ms. If the T is set to 81.13 ms when $M = 1,000$, P_{total} is 0.1609 mW, which is 33.65 % larger than 0.1203 mW, which is the lowest P_{total}. On the other hand, using I-MAC, a longer wakeup period will reduce the power consumption. This trend remains the same irrespective of the number of neighboring nodes. Therefore, using an I-MAC, one could set as large a wakeup period as the allowable range of time delay. Additionally, with I-MAC, less clock drift engenders greater reduction in the total power consumption.

Fig. 8 shows the total power consumption P_{total} against the average number of transmissions M a day per node, where the number of time synchronization C is 50, the number of neighboring nodes N is 10 and the wakeup period T of I-MAC is 500 ms. The LPL limitation curve in the graph portrays the total power consumption when the most appropriate wakeup period is selected for the number of transmissions M. In I-MAC, the total power consumption can be reduced more by reducing the maximum clock drift. If the clock drift per day, D, is 100 ms, then I-MAC can reduce the total power consumption level more than the least power consumption that LPL can offer. Using a clock drift correction algorithm, I-MAC can reduce the clock drift, which works with time synchronization. In light of these facts, which were examined in this study, we can say that I-MAC is superior to LPL.
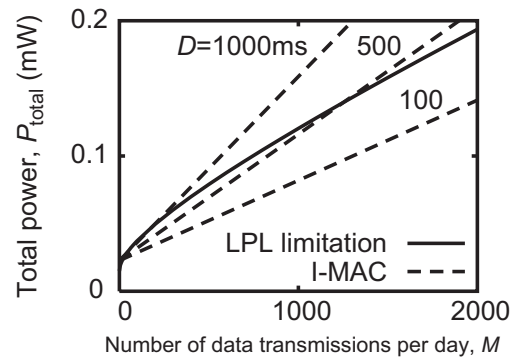

Figure 8.   Impact of the number of data transmissions on total power ($D = 100$, 500 and 1000 ms)

VII.   CONCLUSION

Based on the existing LPL, we have proposed I-MAC, which synchronizes the time using low-frequency radio waves. High sensitivity to the most appropriate length of wakeup period is offered by LPL. That sensitivity helps reduce the power consumption greatly for the certain number of neighboring nodes and for its data transmission frequency. For that reason, its wakeup period must be set carefully. On the other hand, using I-MAC, the wakeup period can be as long as possible within the allowable range of delay time, thereby establishing communication between the sending node and the receiving node. Moreover, I-MAC allows each associated node to correct its clock drift without difficulty; time-synchronization is performed regularly using external signals.

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