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センサネットワークのための長波帯標準電波時刻同期を用いた周期起動型MACの提案

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あらまし　本稿では，センサネットワークのためのメディアアクセス制御として，長波標準電波時刻同期を用いたマルチホップ通信可能な I-MAC（Isochronous-MAC）を提案する．I-MAC は Low Power Listening 方式をベースに，長波標準電波時刻同期によりノード全体が同じタイミングで起動する．受信ノードの起動時刻が予想できるため，LPL に比べてプリアンブル長を短くでき，消費電力を削減できる．本論文では，時刻同期に必要な消費電力オーバヘッドを考慮した解析モデルにより，起動周期，クロックドリフト，時刻同期頻度が消費電力に与える影響を調査した．その結果，LPL は，送信範囲内ノード数，データ送信頻度に対して最適な起動周期の感度が高く，起動周期の設定を注意深く選択する必要があるのに対し，I-MAC は，起動周期の選択が容易であり，時刻同期に要する消費電力を考慮しても LPL に対して消費電力を低く抑えることができることを明らかにした．

キーワード　センサネットワーク，メディアアクセス制御，時刻同期，低消費電力，間欠動作

Isochronous MAC using Low Frequency Radio Wave Time Synchronization 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 radio controlled clocks, 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. 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.

Key words　Wireless Sensor Networks, Media Access Control, Time Synchronization, Low Power, Cycled Receiver

1. INTRODUCTION

A wireless sensor network comprises multiple small wireless sensor nodes, each of which is driven by a limited battery capacity. 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.

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 Low Power Listening (LPL) [1] and WiseMAC [2], 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.

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. To our knowledge, only the effect of the downlink from an access point to a sensor node seems to have been examined with WiseMAC.

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. 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.

Now we will describe the structure of this paper. Section II will describe I-MAC in general. Section III will describe its mathematical modeling for the evaluation. In section IV presents the numerical results we obtained. Finally, we present our conclusions in Section V.

2. GENERAL DESCRIPTION of I-MAC

2.1 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.

One piece of time code information that includes the information of time is sent in one minute. To ensure current time synchronization, a few pieces of time code information are received normally. The time difference that results from this method using the base radio station is 1.5 μs. For that purpose, one-chip LSI (ML6191-A03; OKI [10]) 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.

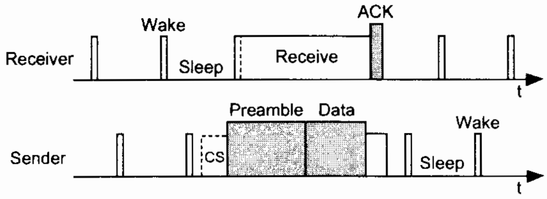
2.2 Isochronous-MAC

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 T_{on}, it reverts to a sleep state.

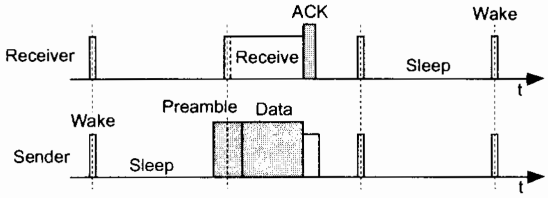
Figure 1(b) shows the manner in which the packet is sent and received when our proposed MAC is used.

To send data, the sender first sends the preamble at the time to wake up the neighboring nodes. The preamble length must be sufficiently long for the other neighboring nodes, including the receiver node, to be able to be wake up. The preamble length is determined based on the time-synchronization timing and the amount of the clock drift.

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 syn-



(a) Low Power Listening



(b) I-MAC

Fig. 1 Low Power Listening and I-MAC

chronization.

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.

3. MODELING of POWER

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 I-MAC is definable with the active time period, T_{total}, and the total consumption energy, E_{total}, as expressed in the following equation.

$$P_{\text{total}} = \frac{E_{\text{total}}}{T_{\text{total}}} \tag{1}$$

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.

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.

$$E_{\text{T}} = P_{\text{rx}} T_{\text{on}} + P_{\text{sleep}}(T - T_{\text{on}}) \tag{2}$$

We define E_{com} as the energy consumed by data sending and receiving; the time T_{com} is required to accomplish that. The entire process happens during T_{total}. Then the energy E_{idle} that is consumed at an idle time during T_{total} can be represented by the following equation.

$$E_{\text{idle}} = \left(\frac{T_{\text{total}} - T_{\text{com}}}{T}\right) E_{\text{T}} \tag{3}$$

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 relative error that is present between the nodes at the synchronization time, and the clock drift varies linearly with time.

$$T_{\text{preamble}} = \frac{4D}{C} + T_{\text{on}} + F \tag{4}$$

Each T_{preamble} causes a change in E_{com} and E_{idle}. Therefore, we respectively define $E_{\text{com-lpl}}$ and $E_{\text{com-imac}}$ for the E_{com} of LPL and I-MAC, and respectively denote $E_{\text{idle-lpl}}$ and $E_{\text{idle-imac}}$ 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

$$E_{\text{sync}} = P_{\text{sync}} T_{\text{sync}} C \tag{5}$$

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

$$E_{\text{total-lpl}} = E_{\text{com-lpl}} + E_{\text{idle-lpl}} \tag{6}$$

$$E_{\text{total-imac}} = E_{\text{com-imac}} + E_{\text{idle-imac}} + E_{\text{sync}} \tag{7}$$

4. 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 $P_{\text{tx}} = 24.75$ mW, $P_{\text{rx}} = 13.5$ mW, and $P_{\text{sleep}} = 0.015$ mW. We used 19.2 kbps as the channel rate, which means that the listening time T_{on} 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 $P_{\text{sync}} = 0.09$ mW, and the time spent to synchronize as $T_{\text{sync}} = 2$ min. Furthermore, the maximum relative time error F was assumed as 3μs.

Figure 2 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 A preamble length can be made sufficiently small by

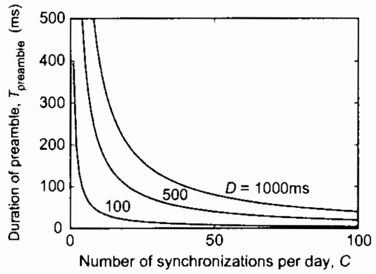


Fig. 2 Relation between duration of preamble transmission and the number of time synchronizations (D = 100, 500 and 1000ms)

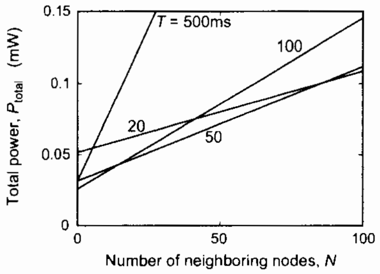


Fig. 3 Relation between the number of neighboring nodes and power in Low Power Listening (T = 20, 50, 100, 200 and 500ms)

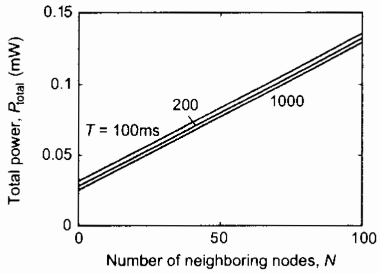


Fig. 4 Relation between the number of neighboring nodes and power in I-MAC (T = 20, 50, 100, 200 and 500ms)

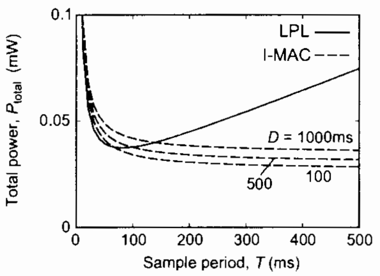


Fig. 5 Relation between wakeup period and power (M = 100, D = 100, 500 and 1000ms)

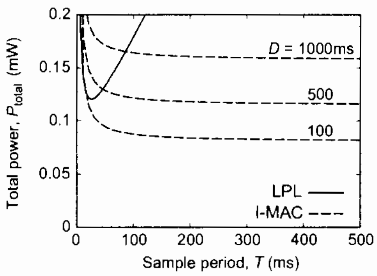


Fig. 6 Relation between wakeup period and power (M = 1000, D = 100, 500 and 1000ms)

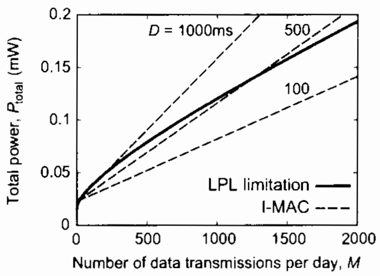


Fig. 7 Impact of the number of data transmissions on power (D = 100, 500 and 1000ms)

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.

Figures 3 and 4 show 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 C is 50. 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.

Next we will specifically examine the sensitivity of P_{total} against M. Figures 5 and 6 show the relationship between the total power consumption and the wakeup period for both LPL and I-MAC, where C is 50 and N is 10. For LPL, there exists an optimum wakeup period that consumes the least power for every 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. On the other hand, using I-MAC, a longer wakeup period will reduce the power consumption. 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.

Figure 7 shows P_{total} against M a day per node, where C is 50, N is 10 and 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 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.

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