An Energy Efficient Predictive-Wakeup Tree-based Multi-Channel Protocol for WSNs

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Abstract

This paper introduces a PWTMCP (Predictive-Wakeup Tree-based Multi-Channel Protocol) which is a new pattern multi-channel protocol in combination with the traditional TMCP and duty cycling power control technology. Firstly, it divides the wireless sensor networks into several sub-trees based on the top of base station and allocates a channel to each sub-tree ,then information flows transmit along the corresponding sub-tree, which eliminates the interference between the tree and avoids the time synchronization problem. Secondly, it uses duty cycling mechanism, which makes the sender accurately predict the receiver's wake up time, thereby reducing the energy consumption of sensor nodes. This paper also adopts the special prediction error correction mechanism that effectively addresses timing challenges such as unpredictable hardware and operating system delays and clock drift. Using prediction-based retransmission ensures the retransmission efficient. Finally, we compare the PWTMCP with the traditional TMCP in the aspect of energy consumption and efficiency of communication, in conclusion that PWTMCP performs better in the dense networks.

Keywords: *PWTMCP; sub-trees; duty cycling; prediction based retransmission*

1. Introduction

The performance requirement of the wireless sensor networks are mainly low power consumption, high stability and low delivery latency, low access latency, high throughput, *etc*. Because of the poor working conditions of sensor nodes, difficulty of replacing the battery, so using energy efficiently to maximize the network life cycle become the focus of the wireless sensor network. Experiments prove that the power consumption of the wireless sensor networks is mainly the invalid idle listening, signal conflict, eavesdropping, control overhead, *etc*. [1]. Most of the energy losses are caused by idle listening. Node keeps on wireless channel idle listening even when it doesn't need to send data in order to receive the possible data. For example, sensor node needs to exchange information with its adjacent node average per second, but the time of exchanging information is very short. The total time of sending and receiving messages is about 10ms. So wireless module uses 990ms for idle listening, this is it does nothing in 99% of time, however, energy consumptions happen almost at this time. Sensor networks' MAC protocols usually adopt listen/sleep alternative wireless channel strategy to solve the problem of idle listening. When there is data to send or receive, the node opens its wireless communication module to send or monitor. When there is no data to send, the wireless communication modules turn into sleeping state, thus reducing the energy consumption caused by idle listening. In order to reduce overhearing and missing the data in sleeping state, adjacent nodes need to coordinate listening and sleeping cycle. Adopting duty cycling mechanism, this article opens wireless transceiver intermittently to save energy through the transformation of sleeping and waking state and uses a pseudo random sequence directly to provide the length of time one wake up to another round. The sender synchronizes the wake up time of receiver according to the receiver's pseudo random function, thus reducing idle listening and improving TMCP's energy utilization.

TMCP has the superiority that it doesn't need synchronization and there is no interference between the sub-trees. However, it also has some disadvantages, such as no power control which causes certain nodes die easily. TMCP is an effective and realistic multi-channel MAC protocol. Traditional TMCP has low communication efficiency within the sub-tree, without considering the energy efficiency and effective collision retransmission. Therefore, it's necessary to improve the TMCP. With the power control of traditional TMCP, the sender can predict the receiver's wake up time to reduce invalid idle listening, and use the minimum power to send messages according to the distance between the source and the host and the status of the current channel, prolonging the network lifetime.

2. Related Works

As the low power consumption characteristics of the wireless sensor network, power control is always important. When the distance between two communication parties is relatively short, small power transmission can reduce unnecessary energy consumption; When the distance between two communication parties is long, compared with a few long distance transmission, adopting multi-hop short distance transmission can cause smaller energy consumption, at the same time it can also effectively reduce the interference and collision on the long distance transmission [2], which makes more nodes on the same channel to transmit at the same time, improving the network communication capacity.

Power control technology reduces the node energy consumption and improves the survival time of network and network throughput. In WSN, only the node not covering each other can be reused in the wireless channel. The more the node's transmission power, the greater the interference range, the lower the channel reusing degree, the smaller the network capacity. Therefore, reducing the transmission power can not only save energy but also increases the network throughput. In WSNs, power control is designed to find the right method to balance the both effect [3], controlling the transmission power according to the specific situation.

Traditional TMCP firstly partition the whole network into multiple vertex-disjoint sub-trees all rooted at the base station and allocate different channels to each sub-tree, and then forward each flow only along its corresponding sub-tree. The superiority of TMCP is two-fold. Firstly, for practical concerns, with a coarse-grained channel assignment, it requires much fewer channels than node-based protocols. Also since every flow is forwarded in one sub-tree with one channel, we do not need a sophisticated channel coordination scheme, which implies that TMCP can work without the need for time synchronization. Secondly, for performance concerns, because it assigns different channels among sub-trees, it can increase network throughput and reduce packet losses by eliminating inter-tree interferences and exploiting spatial reuses of parallel transmissions among sub-trees.

3. The Improved PWTMCP

3.1. The Outline of PWTMCP

PWTMCP has three components, Channel Detection (CD), Channel Assignment (CA), and Data Communication (DC).The CD module finds available orthogonal channels which can be used in the current environment. To do this, two motes are used to sample the link quality of each channel by transmitting packets to each other, and then among all channels with good link qualities, non-adjacent channels are selected. The CA module partitions the whole network into several sub-trees and assigns one unique channel to each sub-tree. We use PMIT algorithm [4] to realize the channel assignment. In this algorithm, we assume that the interference sets of all nodes are already known. This algorithm firstly applies a Breadth-First search algorithm to compute a fat tree rooted at the base station [5]. Nodes keep their height and have multiple parents on the fat tree, which is actually a shortest path tree, where branches from the base station to each node are paths with the least hop count. Next, we execute the channel allocation one-by-one from top to bottom on the fat tree. At each level, we always process nodes with fewer parents first, because they are less free to choose channels. For each node, we choose an optimal channel, in other words select an optimal tree to add the node in. The criteria is that the tree must be connected to the node, and adding the node brings the least interference to this tree. If multiple trees tie, the tree with fewer nodes is chosen. After a node joins a tree, it selects a parent which has the least interference value among all possible parents within the tree selected. It is clear that the algorithm covers all nodes of graphs, and when a node gets a channel, the algorithm ensures it connects to one tree, which demonstrates the correctness of the algorithm. Figure 1 is the PWTMCP's network topology.

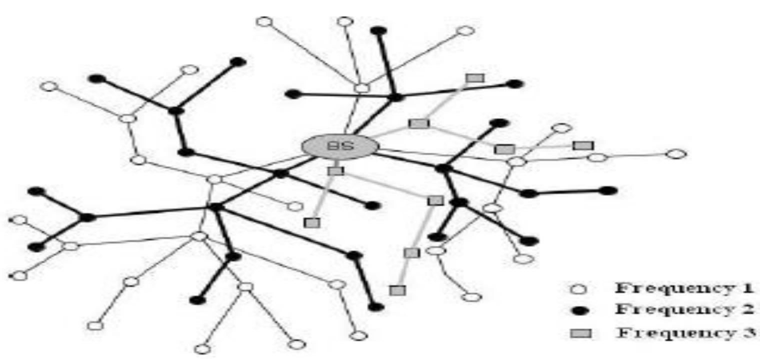

Figure 1. PWTMCP's Network Topology

In order to reduce the idle listening and overhearing within the PWTMCP data communications between sub-trees, we adopt duty cycling technology, each node in the transformation between active and sleep states, opening the wireless transceiver intermittently. The proportion of the awake time is called duty cycle. Node sends beacon to inform its potential sender that it is awake and ready to receive packets. After receiving awakening beacon from the receiver R, S transmits data to R. Then R sends an ACK beacon to S to confirm the receiving data packets, while allowing the other packets to send. If there are no packets to send, the node S and R turn into sleeping state. Each node's waking time is a pseudo random.

3.2. Predictive Wake up Mechanism

The generation of pseudo random sequence can be used to any kind of pseudo-random sequence generator. Because of the LCG convenient for computing and storage, we chose linear congruence generator. LCG generate pseudo random sequence $X_{n+1} = \left(aX_n + c\right) \bmod m$, m is the modulus, a is the multiplier, c for incremental, X_n as the current value, X_{n+1} for the next value. Our experiment sets m for 65536, a and c of each node in accordance with the principles of literature [5] separately, so that the pseudo random sequence is not repeated and cover completely. Different nodes have different parameters for their pseudorandom number generators to avoid nodes persistently generating the same numbers. The sender can predict the receiver's wake up time according to the receiver's predictive state information. If the m, a, c and X_n of the pseudo random number generator of a node R are learned by another node S, S can deduce the values of all future pseudo-random numbers generated by R. When R uses these pseudo-random values as its wakeup intervals and S has learned the time difference between S and R’s clocks, S can deduce all future wakeup times of R and wake up right before R does any time S needs to send a packet to R. Owing to its small memory and message over head and its ability to maintain high energy efficiency under multiple concurrent traffic flows, PW-MAC scales well in large and dense networks.

Figure 2 shows PWTMCP's specific predictive wake up mechanism. Each node in the sub-tree broadcast a beacon (marked as B in figure), notify its waking state and be ready to receive the data. Node R's waking time interval is determined by pseudo random sequence which is generated by the front formula of linear congruence pseudo random generator, and each node has its own parameters. S masters and updates the adjacent node R's prediction state when necessary. When S has a packet (*e.g.*, from the network layer) to send to R, S does not have the prediction state of R, S turns on its radio and waits for a beacon from R. After receiving R’s beacon, when S transmits the DATA packet, S then sets a special flag in the DATA packet header to request R’s prediction state. Once R receives this DATA packet, R sends another beacon that serves both to acknowledge the DATA packet reception (*i.e.*, an ACK beacon) and to allow additional DATA packets to be sent to R, in response to the prediction state request from S, R also embeds its current time and prediction state in the beacon. The current time of R is used by S to compute the time difference between S and R’s clocks. In order to precisely determine this time difference, the current time and prediction state of R are added to the ACK beacon immediately before the packet is sent by R. As soon as the radio hardware of S receives the ACK from R, S computes the time difference between S and R to minimize the error of time difference caused by the sensor node’s operating system delay.

Received the ACK beacon of prediction information, node S can predict R's future wake up time. If S has another packet to send, S wakes up shortly before the predicted wake up time of R, then sent data package to R directly. Unlike sleeping scheduling [7] the sender keeps awake in average half a wake up interval, waiting for the receiver before data transmission. The duty cycling we adopted reduces this idle listening time to almost 0 once the prediction state of the intended receiver has been learned by the sender, greatly improves energy efficiency.

3.3. Predictive Retransmission

In the actual PWTMCP networks, energy efficient data retransmission is very important. Wireless sensor network congestion may be in multiple nodes and may cause wireless transmission collision at the same time. As the actual network is intensive, hidden terminal problem brings conflict which makes the node retransmit. If the hidden terminal conflict after retransmission continues to happen, networks get into a vicious cycle. Furthermore the interference can also cause the retransmission. The retransmission mechanism we adopted can achieve high energy efficiency even in the above situation.

With existing energy-efficient asynchronous duty-cycling MAC protocols, the senders after a collision will do a short back off and retransmit the DATA packets. This way of conducting retransmissions may significantly increase sender duty cycle since, after the collision, receivers may have gone back to sleeping state since they have not received valid packets or they regard the packet transmission as completed, therefore making these retransmissions futile. For instance, after packet transmission failures, senders in RI-MAC stay awake until receivers wake up again, leading to large sender duty cycles. Disregarding the state of the receivers, senders in Wise MAC repeatedly retransmit the packets until the packets are acknowledged, potentially causing further wireless collisions and large sender duty cycle. In contrast, senders in PWTMCP achieve high energy efficiency even when packets have to be retransmitted, by detecting wireless collisions, switching to sleeping state and intelligently choosing when to wake up and retransmit the packets. If the sender S receives wake up beacon rather than ACK beacon from R, S will realize that either the DATA packet or the ACK beacon transmission has failed. S then switches to sleeping state and wakes up at the next predicted receiver wake up time to retransmit the DATA packet, thereby minimizing the energy consumed on waiting for the receiver.

3.4. Prediction Error Correction

We define the wake up prediction error for a node R as the difference between the actual wakeup time and the predicted wakeup time of R. Controlling prediction error is an important issue because if a receiver wakes up before the predicted wakeup time, the sender will miss the wakeup of the receiver, prolonging the packet delivery latency at least by a full wakeup interval and significantly increasing the sender’s duty cycle. On the other hand, if a receiver wakes up much later than the predicted wakeup time, the sender duty cycle will also increase, since the sender then has to remain awake until the receiver does wake up. On the other hand, if the receiver is later than predicted wake up of time, the sender's duty cycle will also increase, because it must keep awake until the receiver wake up. Literature [10] shows that the prediction error is mainly composed of clock drift, operating systems and hardware delay factors and so on. When a node keeps awake and another node adopts the duty cycling, measuring the wake up time of another node, the hardware and operating system delay prediction error is about 10ms; When two nodes all adopt the duty cycling , the prediction error is about 20ms [11, 12]. Therefore, we use a parameter called wake up advance time to solve the time delay of hardware and operating system, the sender will adjust the advance time according to the clock drift. According to this prediction error correction mechanism, once it detects that the prediction error is larger than the sender wakeup advance time, a node S requests an update of the prediction state of another node R. Once the node detects that the prediction error is greater than the correct threshold, it quickly recovers the ability to precisely predict the other node wake uptimes. With this prediction error mechanism, the sender can effectively control the receiver's error to be within its wakeup advance time. This article set the advance time of 20ms to offset prediction error caused by the hardware and the operating system time delay, reducing the chance of the sender missing the receiver.

3.5. Power Control Technology

In addition to sleep scheduling, power control methods had better to be utilized [13]. For an efficient power control method, communication nodes must satisfy the following prerequisite: the physical layer should be able to transmit data frames by the power specified by the MAC layer; the physical layer should be able to tell the MAC layer of the power of the received data frame; the link is bi-symmetrical, and the quality of the link within the duration of one super frame remain unchanged.

The distance between the receiving node and the transmitting node is denoted by d, the power of a data frame transmitted in transmitting node is denoted by P_t, and the power of this data frame received in receiving node is denoted by P_r.Then:

$$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^n g_t g_r$$

Where λ is the carrier's wavelength determined by the carrier's frequency, *i.e.* $\lambda = c/f$ and g_t, g_r separately denote the transmission antenna gain and the receiving antenna gain. n is the channel fading coefficient. The study of indoor radio propagation showed that the value in the hallway or interior open space is approximately 2, while it can reach up to 6 in the metal building. Although we don't know the parameters d and n's specific values in accordance with the change of environment, we can assume they are constant in a short time. Therefore if the transmitting node knows the transmitted signal power P_r and the energy threshold P_{r_thre} for decoding correctly, and it can measure the received signal power P_t we can gain the minimal transmitted power of the receiving node that make sure the receiving node can receive correctly,

$$\mathrm{P}_{t\_\min} = \frac{P_{r\_thre}}{g_t g_r} \left(\frac{4\pi d}{\lambda} \right)^n \quad \mathrm{P}_{t\_\min} = \frac{\mathrm{P}_t P_{r\_thre}}{P_r}$$

To overcome the inaccuracy of estimation brought by the fading channel, a coefficient C can be added on the basis of the above formula, where coefficient C is determined by experiment.

Assuming in PWTMCP sub tree all broadcast packets are transmitted by maximum power transmitted on the control channel, and the unicast packets are transmitted by appropriate power on data channel of the transmission node, the node can obtain the local reception power intensity. The maximum transmitted power of the broadcast packet is a fixed value in all nodes. Since the broadcast packet is transmitted in a fixed default value, after the node obtains its reception power intensity, the appropriate transmit power value satisfies the local minimum reception power can be calculated,

$$P_{t\_prop} = C \frac{P_{\max} P_{r\_thre}}{P_{r\_\max}}$$

where P_{t_prop} is the appropriate transmit power, $P_{r\_\max}$ is the maximum transmit power, P_{r_thre} is the threshold of the node's received power, $P_{r\_\max}$ is the power received by the receiving node when the receiving node sends the maximum power.

The frequent change of the power has influence on upper layer .To reduce this effect, the transmission power can be divided into several levels depending on their values, only when the node power changes across different levels and continues for a certain time, the upper level changes the network topology and routing correspondingly. Because control packets are transmitted through broadcast on the control channel, each node knows the network topology depending on the maximum transmission power of the node, thus can ensure the network connectivity.

4. Simulation

We assume that the communication between the two nodes is regular and sub-trees of TMCP adopt ordinary transmission mechanism. Before we send data, we must test the condition of the receiver R. If it is free, we send the data, and otherwise, we continually monitor the condition, and send the data as soon as it is free. PWTMCP adopt the above duty cycling mechanism. We use MATLAB to build the model and compare the delivery latency and energy consumption respectively. The simulation result is presented at Figures 2 and 3.

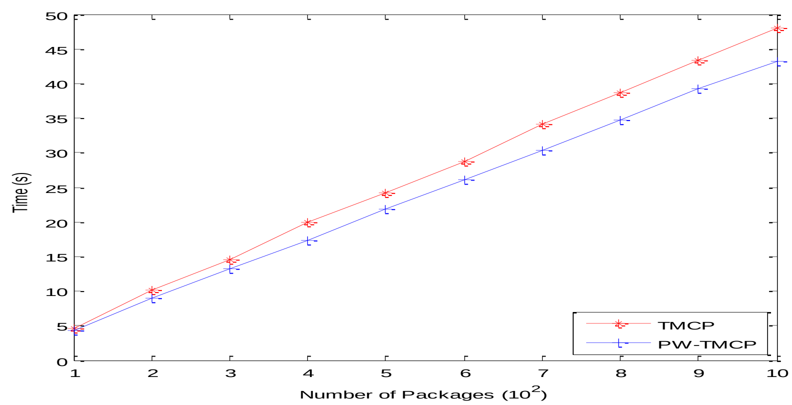

Figure 2. Average Delivery Time

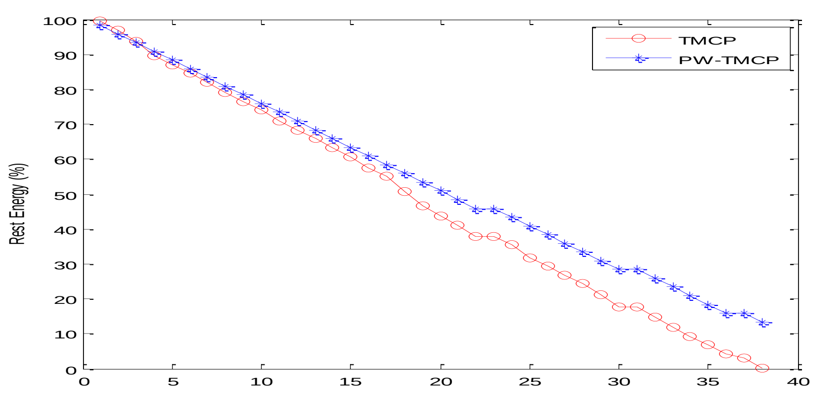

Figure 3. Average Energy Consumption

5. Conclusions

The simulation results indicate that PWTMCP has insurmountable advantages in the aspects of energy efficiency and low-latency. It takes advantages of TMCP, which does not have to synchronize and have no interference among sub-trees. We combine power control with duty cycling mechanism based on pseudorandom sequence, which improves the network throughput and prolong the network's lifetime. We give every node a different pseudorandom sequence and adopt predictive retransmission mechanism, which efficiently reduce the chance of conflict and the time of retransmission.

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