A Low-latency and Energy-efficient TDMA Protocol for Wireless Sensor Networks

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Abstract

In order to solve the problem that BMA protocol has idle listening and large energy consumption, and E-BMA protocol has high latency of data transmission, a new MAC protocol named LL-BMA (Low-latency Bit-map-assisted) was proposed, which maintain high energy efficiency basically and reduce transmission latency significantly as well. To reduce idle listening of contention period and latency of data transmission, this protocol divided the process of node reserve data slot into two ways, making reservation through piggybacking and making reservation through contention period. We compared LL-BMA among TDMA, BMA and E-BMA, the result shows that LL-BMA protocol can compromise relationship of latency and energy efficiency, only a fraction of energy consumption can it reduce the latency of data transmission effectively.

Keywords

Wireless sensor networks; MAC protocol; Low-latency; Energy-efficient.

1. Introduction

WSN (Wireless Sensor Networks) is an intelligent private network which composed of a large number of sensor nodes with specific functions through the wireless communication mode of self-organizing, it can transmit information mutually, complete the specific functions cooperatively, and has been widely used in military, environmental, medical , household, industrial, etc. [1]. Usually, wireless sensor network includes sensor nodes, sink nodes and end users. It combines sensor technology, embedded technology, communication technology, distributed information processing technology, microelectronics manufacturing technology and software programming technology, which can achieve monitor, perceive and collect information of all kinds of environment and monitoring objects within the network monitoring area real-timely, and transmit the processed information to the end users[2].

In wireless sensor networks, MAC (Medium Access Control) protocol determines the usage mode of wireless channel, the wireless channel establishes reliable point-to-point or point-to-multipoint communication link by allocating limited resources between sensor nodes. MAC protocol is the underlying protocol, which has a great influence on the performance of network. The design of the protocol is one of the key factors to determine the communication efficiency of wireless sensor networks[3].

2. Related Work

In the traditional TDMA (Time Division Multiple Address) protocol [4][5], the transmission channel is divided into multiple time slots, each node only wake up to transmit data in the allocated time slot and remain in sleep mode at the remaining time slots, as shown in Figure 1, TDMA can effectively avoid the data collision caused by channel competition [6][7]. However, when the traffic is low, no matter whether there has data to send or not, the source node will still awakened in the allocated time slot, and the cluster head (CH) is always in the wake state, which increase idle listening directly and cause a lot of waste of energy [8].

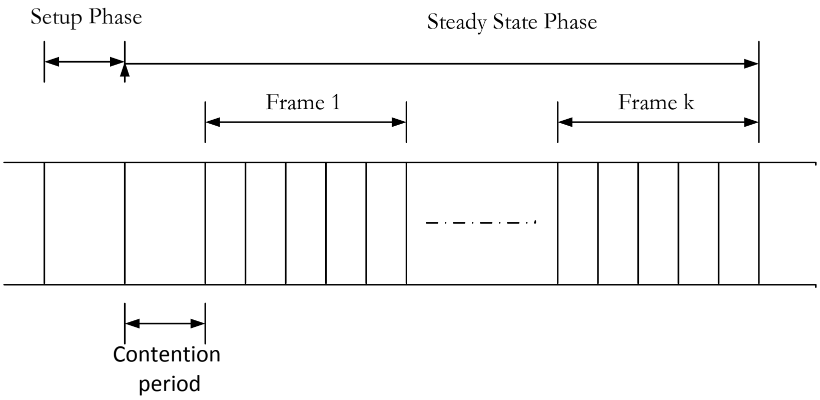

Fig. 1 A single round of TDMA protocol.

To solve this problem, Li Georgios and Y. Lazarou Jing made a great improvement on TDMA, and put forward the BMA (Bit-map-assisted) protocol [9]. Figure 2 describes a single round for BMA, each frame of the protocol contains a contention period and has an assignment of time slot. In the contention period, all nodes keep their radio on, each node has an allocated time slot. When there has a data packet to send, the source node sends a 1bit control message to the CH, then the CH assigned data slots to these nodes, each source node only has one data slot per frame. After all source nodes sent the data packet in turns, the CH enters the sleep state until the next frame starts [10].

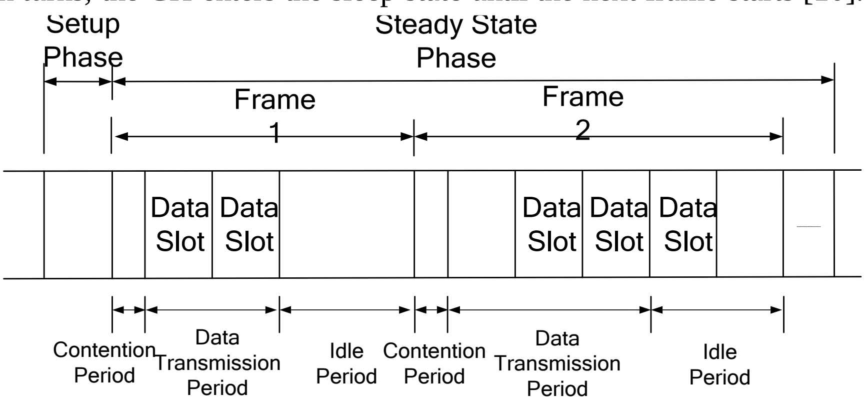

Fig. 2 A single round of BMA protocol.

To further reduce energy consumption, G M Shafiullah et al. improved the way of node making reservation of data slot on the basis of BMA, and proposed a new protocol named E-BMA (Bit-map-assisted Energy-efficient) protocol [11]. As shown in Figure 3, the protocol is set to event driven, the sensor node forward data packet to the CH only if a significant event happen. When a significant event occurs, the source node does not make reservation in the contention slot immediately, instead, it wait an additional frame to confirm whether there has successive data packets to transmit by allocating 1bit packet header for each packet. If a source node has successive data packets to send in a number of consecutive frames, the reservation is only made in the initial data packet's allocated contention slot, and the successive confirmations will be made through piggybacking [12]. Thus, in the next contention period, the source node does not need to send the control message, the radio is off, which makes the energy efficiency of E-BMA is better than BMA. But the wait of additional frame increase the latency of data transmission significantly.

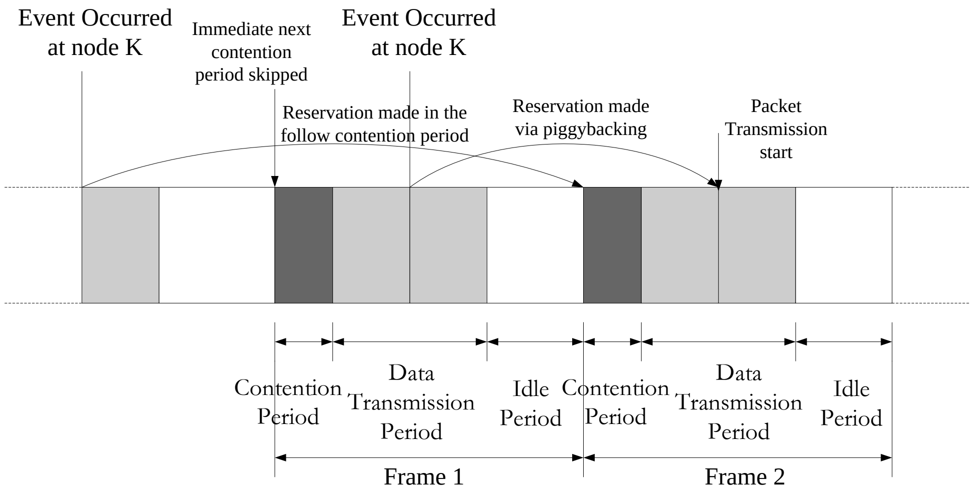

Fig. 3 A single round of E-BMA protocol.

3. LL-BMA Protocol

In BMA, CH keeps radio on all the contention period, cannot achieve a good energy efficiency; E-BMA reduces the idle listening of CH through piggybacking, it has to wait for an additional frame but before sending each packet, the data transmission latency will be increased. In order to balance the relationship between latency and energy efficiency, a low latency and high efficiency MAC protocol based on the both BMA and E-BMA named LL-BMA (Low-latency Bit-map-assisted) protocol is proposed. This protocol is set to event driven [13], which can change the way of source node reserving data slot dynamically to reduce latency of data transmission while ensure high energy efficiency.

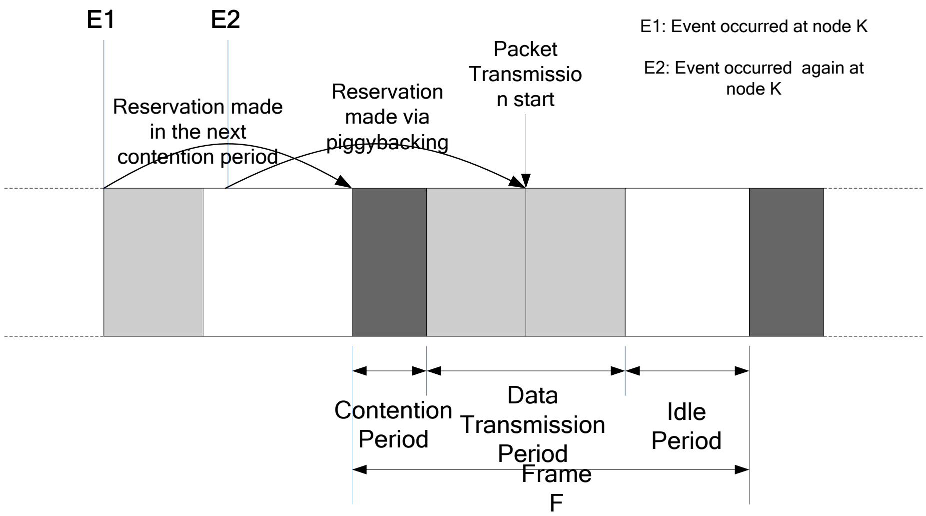

Fig. 4 A single round of LL-BMA protocol.

As in LEACH [14], the LL-BMA is divided into rounds. Each round consists of a setup phase and a steady state phase. The steady state phase is composed of a contention period and a data transmission period. The description of a single round for LL-BMA is showing in Figure 4. The formation of cluster and the selection of CH occur in the setup phase, the non-CH nodes make reservation in the contention slot and forward data packets to CH in the data slot.

3.1 Setup Phase.

The selection of LL-BMA is the based on the proportion of CH in the network and the times that each node has been selected as the CH [15], just as in LEACH, each sensor node selects a value between 0 and 1 randomly, if the selected value is less than the threshold value $T(n)$, then the node becomes a CH, the $T(n)$ can be described as:

$$T(n) = \frac{p_{CH}}{1 - p_{CH} * (r \bmod \frac{1}{p_{CH}})}, \forall n \in G \tag{1}$$

$$T(n) = 0, \forall n \notin G \tag{2}$$

Where n is the giving number of nodes, p_{CH} is the proportion of CH, r is the number of the round currently, G is the set of nodes which was not selected as CH in the last $1/p_{CH}$ rounds. Using this threshold, nodes will be selected as the CH in the $1-p_{CH}$ rounds. After $1/p_{CH}-1$ rounds, $T(n)$ of all nodes is l, then there has no CH to be selected.

After this selection, each CH broadcast to the whole network. Other nodes in the network determine the dependent cluster according to the signal strength of the received information, and use the CSMA to notify the corresponding CH.

Suppose that the network comprises a plurality of fixed clusters, each cluster has only one CH in the center of the cluster, the source nodes communicate to the CH directly, rather than using multi-hop data communication mode, as shown in figure 5. During the setup phase, the CH broadcast to all nodes about the start of the current round, the start and stop time of the frame and number of frames in a round[16].

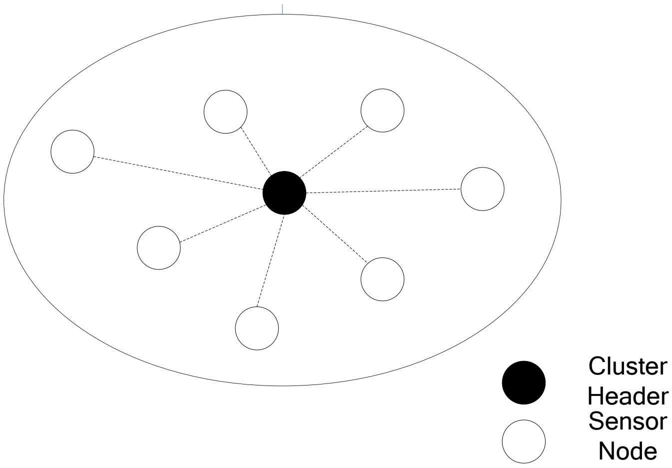

Fig. 5 A cluster with one CH and N sensor nodes.

3.2 Steady State Phase.

In the steady state phase, the sensor node transmit data packet to CH. The CH aggregates the data packet and reduces unwanted data before sending to the base station or the central controller. This phase contains contention period and data transmission period [17] [18].

Contention period: In the contention period CH assigns a specific time slot to each node. When a specific driven event occurs at the node K (i.e. E1), the node sends a 1bit control massage to make reservation of the corresponding data slot in the next frame (i.e. F). There has a 1bit field allocated in each packet header. When the specific driven event occurs again in node K (i.e. E2), using the 1bit filed of E1, the successive confirmation of E2 will be made through piggybacking. After the end of contention period, CH set up and broadcast a transmission schedule to all source nodes, the source nodes transmit data packets to the CH in their assigned data slots. Since the position of E2 is randomly, the source nodes should select whether it can be piggybacked or not dynamically according to the position of E2, thus it is divided into the following two cases:

1) E2 occurs before the start of the frame F, and it can be piggybacked:

The data packet can be send successively without waiting an additional frame, E1 makes reservation directly in the contention period of frame F and piggybacks a 1bit packet header to make reservation of E2. Nodes turn off their radio when there has no control message to send and turn into sleep mode to reduce the energy, also the waiting time of the data packet transmission is reduced.

2) E2 occurs after the start of the frame F, and it cannot be piggybacked:

E2 happens too late and cannot make reservation through piggybacking, it can only make reservation in the next contention period by sending a control message. In this case, the node can reduce the transmission latency, although there has a small part of energy consumption.

The process shown in Figure 6:

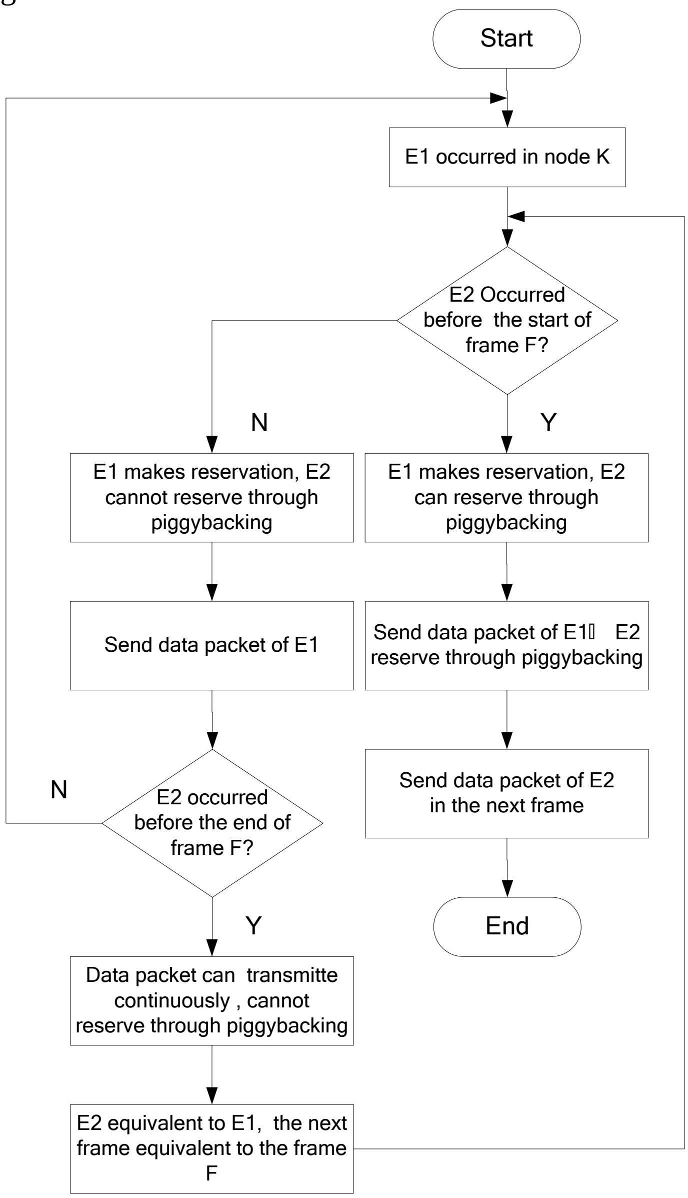

Fig. 6 The process of node K.

Data transmission period: This period contains one or more data slots. The size and duration of each time slot is fixed. During the data transmission phase, the source node turns on its radio in the allocated time slot, and forwards data packet to CH, it can only send one data packet at most per frame. After all source nodes sending their data packets, it turns into idle period until the next frame start or node is awakened by a particular driven event.

After receiving the data packets from all source nodes in the current round, the CH processed locally to reduce unwanted data. Comparing with transmit all data to base station or central controller, it can save a considerable amount of energy. Then the resultant data are sent from CH to base station using a spreading code and a CSMA approach, as used in LEACH. Before sending, CH must sense the channel to see if the channel is occupied. If the channel is occupied, the CH waits until the channel is idle. After a predetermined period of time, the system starts a next round, and the whole process is repeated.

4. Analytical and Simulation Modeling.

Assuming that there are only one CH and N non-CH nodes in each cluster, l frames per round, the time required to send or receive a data packet, a control packet and a scheduling information is T_d, T_c and T_{ch}. The probability that the node has data to transmit is p. The energy consumption of transmission mode, reception mode and idle listening is P_t, P_r and P_i. The energy consumption of the contention period, data transmission phase and the whole round is E_{cont}, E_{frame} and E_{trans}.

4.1 TDMA Protocol.

In the contention period, all nodes keep their radio on, and the communication happens between CH and non-CH nodes. The CH allocates data slot for each node to transmit data packet and broadcasts to all nodes in the cluster. Therefore, the energy consumption of CH to send scheduling information is P_tT_{ch}, and the energy consumption of each node to receive scheduling information is P_rT_{ch}. The energy consumption of the contention period is:

$$E_{cont-TDMA} = NP_rT_{ch} + P_tT_{ch} \tag{3}$$

Each node can only transmit one data packet at most in each frame. The energy consumption of the source node to transmit a data packet is P_tT_d per frame, and the energy consumption of CH to receive a data packet is P_rT_d. Non-source nodes turn on their radio to keep listening in the allocated time slot, the energy consumption is P_iT_d. In the data slot, when there has no data packet to receive, CH keep idle listening, the energy consumption is P_iT_d. The probability that a node has a data packet to send is p, while keep idle listening is $1-p$. Each round has l frames, then the whole transmission energy consumption is :

$$\mathrm{E}_{trans-TDMA}=[pP_tT_d + (1-p)P_iT_d + pP_rT_d + (1-p)P_iT_d]lN \tag{4}$$

Therefore, the average energy consumption per round for TDMA is:

$$\mathrm{E}_{TDMA}=[NP_rT_{ch} + R_tT_{ch}]+[pP_tT_d + 2(1-p)P_iT_d + pP_rT_d]lN \tag{5}$$

In TDMA, nodes only transmit data packet in the allocated time slot, so the maximum transmission latency is $T_{ch} + NT_d$.

4.2 BMA Protocol.

BMA has a contention period in each frame with all nodes keep their radio on. The source node broadcast a control message in the allocated time slot, and remains listening in the other N-1 time slots. Each non-source node remains listening throughout the whole contention period. Each source node sends a control message to CH in the contention period, the CH keep listening even if there has no data packet need to be received. The energy consumption of BMA in the contention period is:

$$E_{\text{cont}-BMA}=[pP_tT_c+(1-p)P_iT_c+(N-1)P_iT_c \\ +P_rT_{ch}]N+[pP_rT_c+(1-p)P_iT_c]N+P_tT_{ch} \tag{6}$$

During the data transmission period of each frame, the source node transmits data packet in the assigned data slot, non-source nodes keep their radio off, and the expected energy consumption is:

$$E_{frame-BMA}=[pP_tT_d+pP_rT_d]N \tag{7}$$

The average energy consumption per round for BMA is:

$$E_{BMA}=[[pP_tT_c+pP_rT_c+2(1-p)P_iT_c+(N-1)P_iT_c \\ +P_rT_{ch}+pP_tT_d+pP_rT_d]N+P_tT_{ch}]l \tag{8}$$

In BMA, each frame has a contention period, thus the maximum transmission latency is $T_{ch}+\left(T_c+T_d\right)N$.

4.3 E-BMA Protocol.

The source node sends control message in the respective contention time slot, and keeps listening in the other N-1 contention time slots, and the node make reservation by piggybacking if it has successive data packets to send. The non-source nodes keep their radio off throughout the whole contention period. If there has no data packets to send in the previous frame, the control message cannot be piggyback. The probability of a data packet not being piggybacked is $p(1-p)$. If the control message is piggybacked, the source node turns off radio in the corresponding contention slot, while the CH keeps idle listening. The expected energy consumption of the E-BMA in the contention period is:

$$E_{cont-E}=[p(1-p)P_tT_c+P_rT_{ch}]N \\ +[p(1-p)P_rT_c+(1-p(1-p))P_iT_c]N+P_tT_{ch} \tag{9}$$

During the data transmission period of each frame, as in BMA, the source node sends data packet in the allocated time slot, and non-source nodes turn off their radio. The expected energy consumption is:

$$E_{frame-E}=[pP_tT_d+pP_rT_d]N \tag{10}$$

The average energy consumption per round for E-BMA is:

$$E_{E-BMA}=\{[p(1-p)P_tT_c+p(1-p)P_rT_c \\ +(1-p(1-p))P_iT_c+P_rT_{ch}+pP_tT_d \\ +pP_rT_d]N+P_tT_{ch}\}l \tag{11}$$

Because of the additional wait before sending each data packet, latency increased significantly. The maximum transmission latency of E-BMA is $2\left[T_{ch}+2\left(T_c+T_d\right)N\right]$.

4.4 LL-BMA Protocol.

In the LL-BMA, nodes make reservation during the contention period or through piggybacking, Piggybacking a control message only need a 1bit field in each data packet. As the location of E2 cannot be determined in advance, according to the mentioned earlier, the probability of a node have data packet to send is p, suppose that the probability of E2 happen before the start of frame F is λ, which is only related with the traffic of network. The expected energy consumption of LL-BMA in the contention period is:

$$E_{cont-LL}=\lambda[[p(1-p)P_tT_c+P_rT_{ch}]N \\ +[p(1-p)P_rT_c+(1-p(1-p))P_iT_c]N+P_tT_{ch}] \\ +(1-\lambda)[pP_tT_c+(1-p)P_iT_c+(N-1)P_iT_c+P_rT_{ch}]N \\ +[pP_rT_c+(1-p)P_iT_c]N+P_tT_{ch} \tag{12}$$

Data transmission period is the same as that of BMA and E-BMA. The source node transmits data packet in the assigned time slots. The non-source nodes keep their radio off. The expected energy consumption is:

$$E_{frame-LL} = [pP_tT_d + pP_rT_d]N \tag{13}$$

The average energy consumption per round for LL-BMA is:

$$\begin{aligned} E_{LL-BMA} &= (E_{cont} + E_{frame})l = \lambda E_{E-BMA} + (1-\lambda)E_{BMA} \\ &= \lambda\{[p(1-p)P_tT_c + p(1-p)P_rT_c \\ &+ (1-p(1-p))P_iT_c + P_rT_{ch} + pP_tT_d + pP_rT_d]N + P_tT_{ch}\}l \\ &+ (1-\lambda)[[pP_tT_c + pP_rT_c + 2(1-p)P_iT_c + (N-1)P_iT_c \\ &+ P_rT_{ch} + pP_tT_d + pP_rT_d]N + P_tT_{ch}]l \end{aligned} \tag{14}$$

In LL-BMA, each node does not need to wait for an additional frame to send data packet, so the maximum transmission latency is $T_{ch} + 2(T_c + T_d)N$.

5. Result and Analysis.

In this paper, we compared LL-BMA with TDMA, BMA and E-BMA to analyze the average energy consumption per round and the maximum transmission latency as the main analysis parameters. In the choice of node model, we select WINS energy node model, if there is no special explanation, the simulation parameters are set as Table 1:

Table 1. Simulation parameter settings

Parameter	Value
P_t	462mW
P_r	346mW
P_i	330mW
Data rate	24kbps
p	0.3
λ	0.3
N	100
l	4
Data packet size	250bytes
Control packet size	18bytes

5.1 Energy Consumption

Figure 7 is the energy consumption analysis of the four protocols under different values of probability λ. (1) The energy consumption of TDMA, BMA, and E-BMA protocols is always a fixed value, while the LL-BMA protocol decreases with the increasing of λ. (2) The TDMA protocol has the highest energy consumption, and the LL-BMA protocol is always lower than BMA protocol but higher than E-BMA protocol. When λ approaching to 0, LL-BMA protocol is close to BMA protocol, while near the E-BMA protocol when λ approaching to 1. Since the location of E2 does not affect the transmission of protocols in TDMA, BMA, and E-BMA, the energy consumption of these protocols is unrelated with λ.

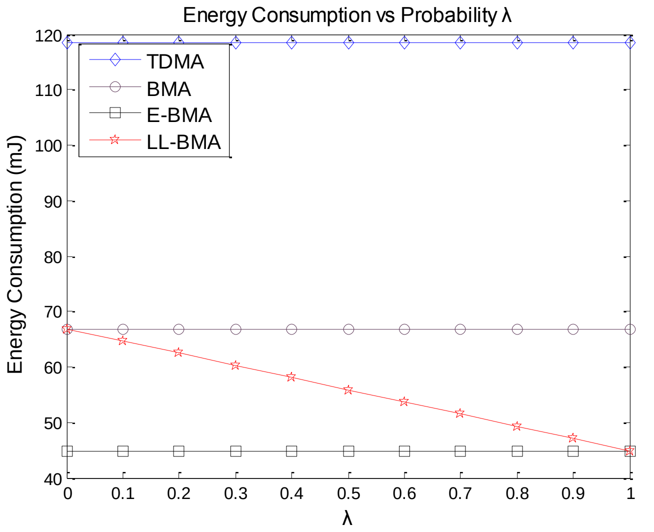

Fig. 7 Energy Consumption vs Probability λ .

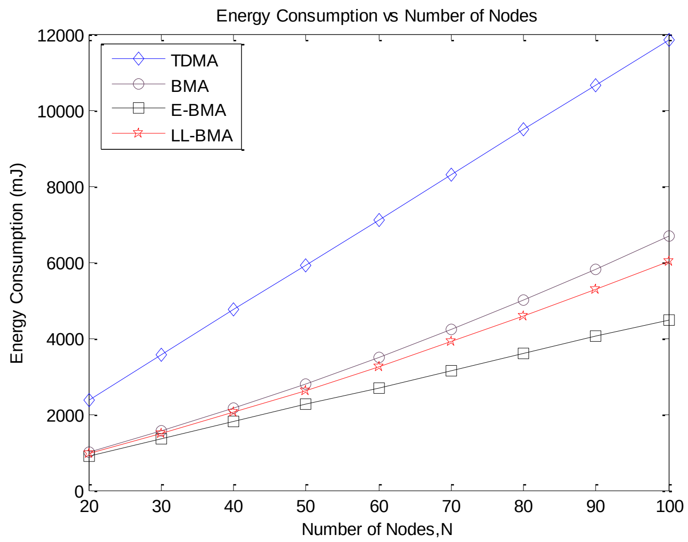

Fig. 8 Energy Consumption vs Number of Nodes.

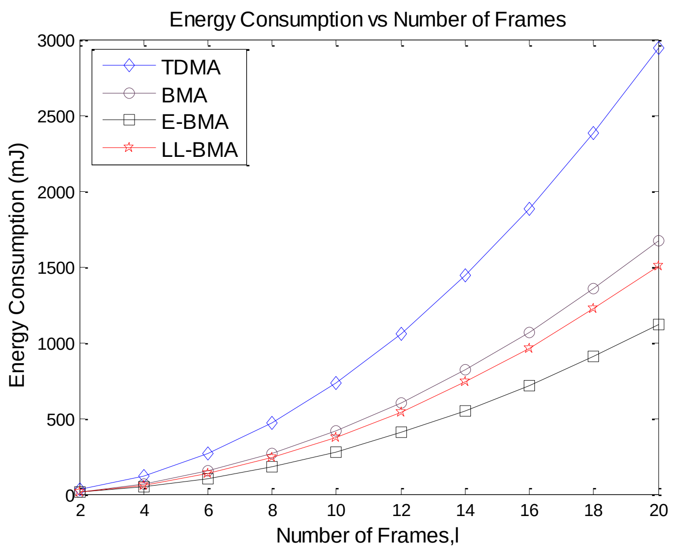

Fig. 9 Energy Consumption vs Number of Frames.

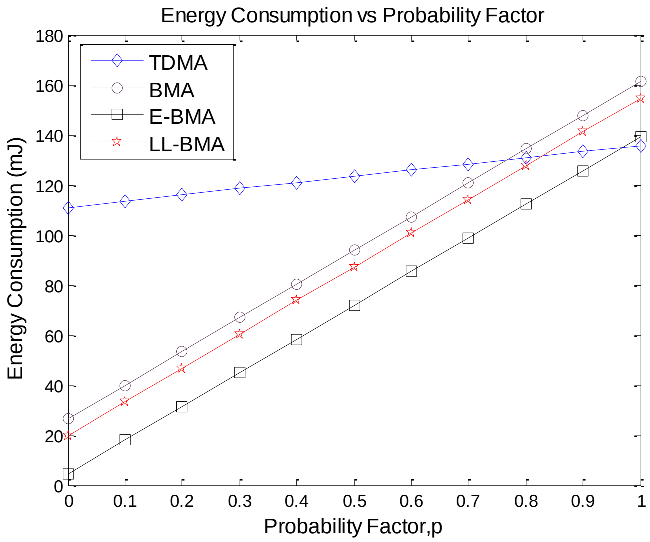

Fig. 10 Energy Consumption vs Probability p.

Figure 8 and Figure 9 are the energy consumption of the four protocols with the number of non-CH nodes N and the number of frames l. It is obviously that (1) the energy consumption of the four protocols increase with the increasing of the N or l, (2) LL-BMA protocol is far less than TDMA protocol, and is always lower than BMA protocol but higher than E-BMA protocol. This is because the LL-BMA protocol combines making reservation in contention period with through piggybacking which cost a small part of energy.

Figure 10 is the average energy consumption with the probability p. (1) the TDMA protocol has a large idle listening, all nodes are always awake, so energy consumption is almost a straight line; (2) when $p < 0.8$, compared with TDMA protocol, the performance of BMA, E-BMA, LL-BMA protocol are better. Because these three protocols reduce idle listening in low to medium traffic load. It can be seen, LL-BMA protocol is more suitable for low to medium traffic load.

Figure 11 is the energy consumption in diffident packet size. Comparing with the data transmission period, the energy consumption of contention period is small and almost can be ignored. Consequently, BMA, E-BMA, LL-BMA protocols have good energy efficiency when the packet size is larger than 50 bytes, but when it is less than 50 bytes, the TDMA protocol is more energy efficiently.

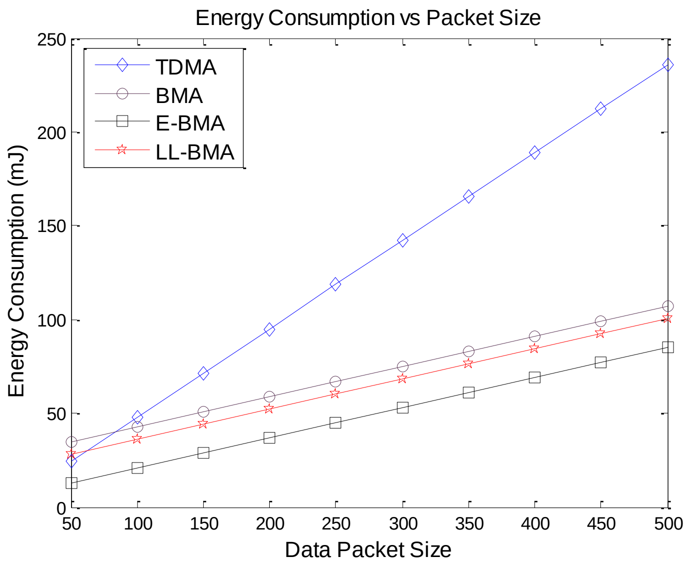

Fig. 11 Energy Consumption vs Packet Size.

5.2 Transmission Latency

The maximum transmission latency of the protocol is only related to the number of nodes N and the size of data packets, since the transmission rate of the data packet is fixed at 24kbps. Therefore, in this paper, the maximum transmission latency is simulated and analyzed from the number of nodes and the size of the data packets. The results are shown in Figure 12 and Figure 13.

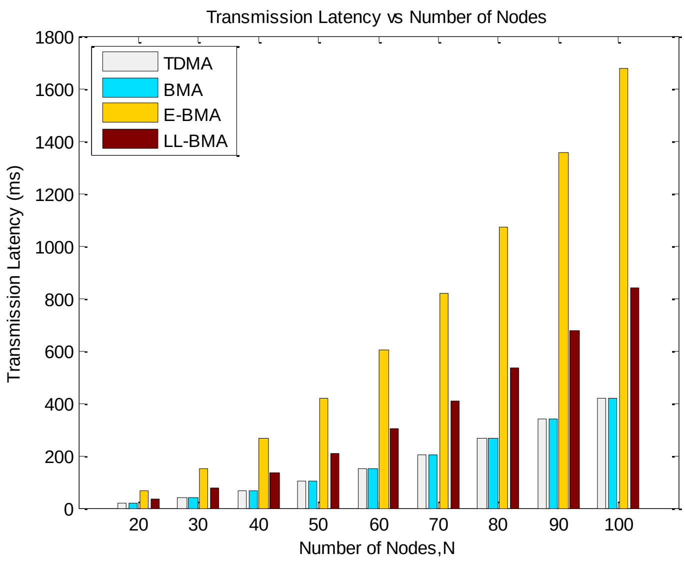

Fig. 12 Transmission Latency vs Number of Nodes.

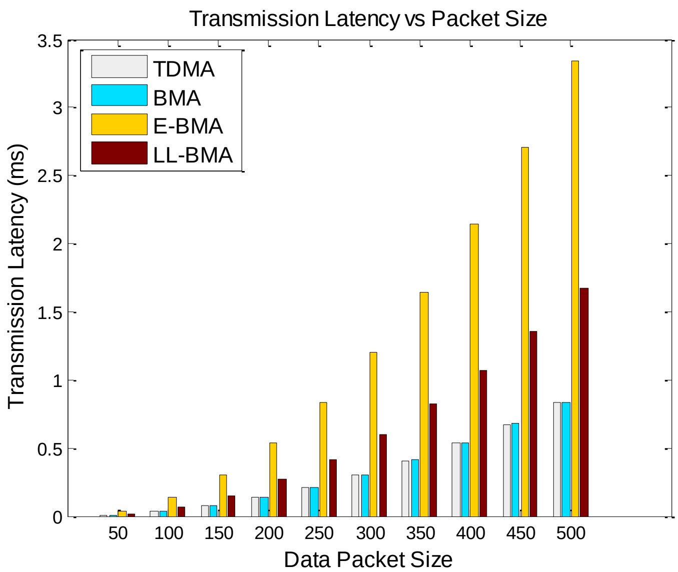

Fig. 13 Transmission Latency vs Packet Size.

The results show that no matter how the number of nodes and the packet size change the latency of LL-BMA protocol is slightly higher than TDMA protocol and BMA protocol. However, compared with E-BMA protocol, the latency is greatly reduced.

Comparing with TDMA and BMA protocol, LL-BMA protocol reduces energy consumption with a small consume of latency. But comparing with EMA, LL-BMA protocol reduces the latency of data transmission with a small consume of energy. Therefore, LL-BMA protocol in low to middle traffic load can maintain low energy consumption greatly and reduce the latency effectively.

6. Conclusion

In this paper, a new MAC protocol with low latency and high energy efficiency named LL-BMA protocol is proposed. Through the mathematical model and simulation analysis, we compared this protocol with TDMA, BMA and E-BMA protocol. The result shows that in low to middle traffic load (i.e. $p < 0.8$), LL-BMA protocol can ensure high energy efficiency and reduces the latency of data transmission at the same time. The next step of the research will analyze in specific applications and combine the communication within the clusters with the communication between the clusters to improve the performance of the network.

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