An Adaptive Energy-Efficient and Low-Latency MAC Protocol for Wireless Sensor Networks

Hao Liu, Guoliang Yao, Jianhui Wu, and Longxing Shi

Abstract: **In this paper, an adaptive MAC protocol (variable load adaptive (VLA)-MAC) is proposed for wireless sensor networks. This protocol can achieve high energy efficiency and provide low latency under variable-traffic-load conditions. In the case of VLA-MAC, traffic load is measured online and used for adaptive adjustment. Sensor nodes transmit packets in bursts under high load conditions to alleviate packet accumulation and reduce latency. This also removes unnecessary listen action and decreases energy consumption in low load conditions. Simulation results show that the energy efficiency, latency, and throughput achieved by VLA-MAC are higher than those achieved by some traditional approaches.**

Index Terms: **Burst transmission, selective wake-up schedule, variable load adaptive (VLA)-MAC, wireless sensor networks.**

I. INTRODUCTION

Wireless sensor networks (WSNs) usually comprise of a large number of battery driven sensor nodes organized in an ad-hoc manner, WSNs have many potential applications such as in surveillance, study of rare-animal habitation, medical systems, and industry control. In typical WSN applications, sensor nodes monitor events in environments and report events to a sink node in a multi-hop style [1]–[2]. Minimizing energy consumption is an important challenge [3] because in most situations, it may be difficult to recharge batteries. Reducing latency is also important since in a lot of applications, when an event is detected, the collected data must be reported as soon as possible so that appropriate action can be quickly taken to reduce unnecessary losses.

Several researchers have provided extensive solutions for achieving high energy efficiency; these solutions are based on carrier sense multiple access (CSMA) [4], [5], time division multiple access (TDMA) [6]–[8] and multi-channel [9]–[11]. One of the major difficulties in current WSNs, however, is that the traffic in networks shows temporal and spatial diversiform characteristics. For example, if sensor nodes detect events in networks and generate packets, then traffic loads in the networks increase suddenly. Furthermore, traffic near the sink is more than that far away from the sink. Many current protocols for WSNs do not exhibit acceptable adaptive ability for variable traffic conditions; in other words, the performance of these protocols is unsatisfactory.

To improve the performance of MAC protocols in variable-traffic-load conditions, several protocols have been proposed recently. Timeout-MAC (T-MAC) [12] introduces a timeout scheme that causes sensor nodes to go to sleep early when no active events occur, thereby reducing energy consumption during periods of low load. However, T-MAC cannot handle the high-load conditions well. Dynamic sensor-MAC (DS-MAC) [13] adopts a variable duty-cycle operation to enhance energy efficiency and reduce latency. However, to reduce synchronization difficulties, its duty-cycle can only be changed to a 2^n style of the basic duty-cycle, or else destination nodes may not receive sync packet correctly, and synchronization is also breakdown. In routing-enhanced (RMAC), as reported in [14], sensor nodes use a pipeline transmission method to deliver packets quickly to achieve low energy consumption and latency. However, RMAC cannot alleviate packet accumulation problems effectively.

These adaptive protocols require sensor nodes to adjust their duty-cycle to suit traffic load; however, they may introduce additional synchronization difficulties under variable-load conditions. If sensor nodes alter their duty-cycles, synchronization with other nodes will be lost since to maintain synchronization, sensor nodes need to send control packets to notify other nodes. When the network scale is large, such duty-cycle adjustment method is a difficult task.

In this paper, we propose an adaptive MAC protocol (variable load adaptive (VLA)-MAC) for WSNs; this protocol can only handle traffic load changes effectively and achieve high performance, but also avoid the introduction of additional synchronization difficulties during variable load conditions. The use of WSNs that are easily implemented is also of importance.

The rest of this paper is organized as follows: In Section II, we describe problems existing in variable-traffic WSNs. In Section III, the proposed VLA-MAC is described in detail. The performance evaluation of VLA-MAC is provided in Section IV, and Section V is the conclusion of the paper.

II. PROBLEM STATEMENT

Traditional MAC protocols for WSNs as sensor-MAC (S-MAC) use a fixed listen/sleep schedule to reduce energy consumption. That is, the cycle length and duty-cycle remain the same.

When sensor node traffic load increases, many packets arrive during a cycle. If sensor nodes cannot send out these packets in time because the nodes are sleeping, packets will accumulate in the buffer queue leading to a long packet latency. Furthermore, if packets accumulate continually and cannot be sent out in a timely manner, buffer queue overflow due to limited buffer capability may ultimately cause a serious deterioration in system performance. Fig. 1 illustrates this problem.

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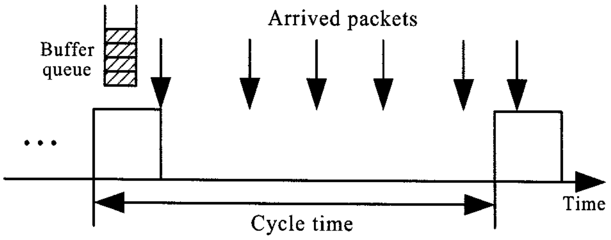


Fig. 1. Packets accumulation.

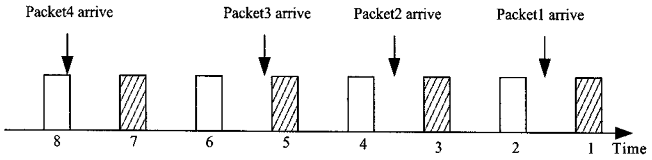


Fig. 2. Unnecessary wake-up action under low traffic load.

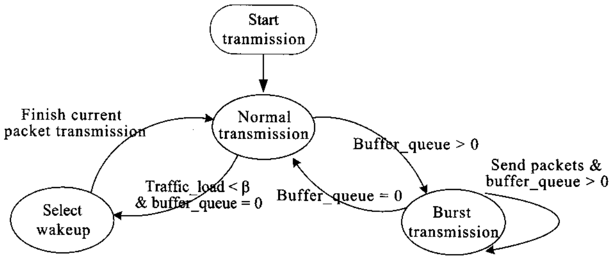


Fig. 3. State machine of VLA-MAC.

On the contrary, when traffic load decreases, packet arrivals in sensor nodes occur relatively infrequently. Under low traffic load, packet inter-arrival time may override several cycles. If sensor nodes still adopt a normal fixed listen/sleep schedule with a constant cycle, unnecessary wake-up action may waste considerable energy. As shown in Fig. 2, traffic load is light and packet inter-arrival time is longer than the cycle time. Therefore, in the active periods 1, 3, 5, and 7, sensor nodes are not required to wake up since no packet arrives during such cycles. If sensor nodes carry out their normal fixed schedule, these wake-up actions may consume considerable energy due to idle listening.

III. VLA-MAC PROTOCOL DESIGN

In this section, we describe VLA-MAC in detail. The design considers adaptive ability and the enhancement of protocol performance in variable load conditions. VLA-MAC sensor nodes follow a listen/sleep schedule to reduce energy consumption. In a similar way to S-MAC, we define a complete listen/sleep period as a cycle, which consists of a listen period and a sleep period. The listen period is further divided into a sync phase and a data phase. Duty-cycle and cycle length are predefined and remain constant. In variable traffic conditions, sensor nodes adopt burst transmission and selective wakeup to handle variable traffic conditions. Since VLA-MAC does not change its duty-cycle, it does not introduce additional synchronization problems under variable load conditions.

The state machine of the VLA-MAC is shown in Fig. 3. If packet accumulation in the buffer is detected, sensor nodes enter the burst transmission state, coming back to the normal transmission state when buffer queue $= 0$. Besides, If traffic load $< \beta$ and buffer queue $= 0$, sensor nodes enter the select wakeup state comeing back to the normal transmission state after current packet transmission.

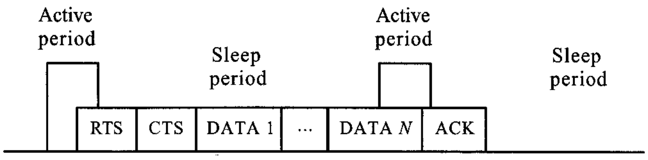


Fig. 4. Burst transmission operation.

A. Traffic Load Estimation

VLA-MAC uses packet inter-arrival time to estimate traffic load. More precisely, a given sensor node records each packet arrival time continuously and calculates traffic load based on packet inter-arrival time, and then uses a low pass filter to average sampled measurements and estimate current traffic load.

Let t_k and t_{k+1} be the previous packet arrival time and the current packet arrival time, respectively, we estimate the sample traffic load as

$$l_{k+1} = \frac{1}{t_{k+1} - t_k}. \tag{1}$$

Letting $\Delta t_{k+1} = t_{k+1} - t_k$, then the sample traffic load can also be expressed as $l_{k+1} = \frac{1}{\Delta t_{k+1}}$. Since stochastic interference may influence packet inter-arrival time, we employ a low pass filter to average sampled measurements and obtain the low-frequency components of the available load.

Letting L_k be the previous filtered estimate of load, and L_{cur} be the current sample estimate of load, the current filtered estimate of load can be expressed as

$$L_{k+1} = \alpha L_k + (1 - \alpha) L_{\text{cur}}. \tag{2}$$

Here, α $(0 \leq \alpha \leq 1)$ is the filter fact, and is usually 0.9.

B. Burst Transmission

In VLA-MAC design, sensor nodes measure buffer queue length before each transmission. If sensor nodes detect more than one packet in the buffer queue, this strongly implies that packet accumulation is occurring. Sensor nodes then transmit packets by using a burst style. Fig. 4 shows the burst transmission operation in VLA-MAC.

In a burst transmission operation, packets are sent using a request to send (RTS)/clear to send (CTS)/DATA 1/DATA 2/$\cdots$ /DATA N/acknowledge (ACK) style. If a given sensor node wants to send packets to its next-hop neighbor, it sends an RTS control packet that includes information about the packet number in a burst transmission (N_{bst}) and the time to the end of the transmission, and to the next-hop address. After receiving the RTS packet, the destination next-hop neighbor returns a CTS control packet to the sender while other overhearing neighbors go to sleep to conserve energy. The sender then sends N_{bst} packets continuously to the next-hop neighbor. After receiving these packets, the destination next-hop neighbor sends an ACK control packet for acknowledgement, ending the current burst transmission.

All the control packets and data packets contain the information about packet numbers and the end time of the current burst transmission, so other neighboring nodes overhearing the control packets or data packets update their network allocated vector (NAV) and go to sleep to save energy. If a burst transmission starts, sensor nodes will continue to send packets until the ACK packet is received, even if the burst transmission duration exceeds a cycle time, as illustrated in Fig. 4.

We defined the maximum packet number in a burst transmission be $N_{\max}$, which is limited by fairness and synchronization requirements. If a sender occupies a channel for too long, other nodes can not send packets during this period and fairness is affected. In addition, if a burst transmission strides several cycles, normal synchronization may be breached. Assuming control packets and data packets have the same transmission speed of k (bytes/s) and all the data packets have the same length, then we let the packet lengths RTS, CTS, DATA, and ACK be L_{RTS}, L_{CTS}, L_{DATA}, and L_{ACK}, respectively. Letting the control packet interval be short interframe space (SIFS) and the data packet interval be PCF interframe space (PIFS), the burst transmission time can be expressed as

$$\begin{aligned}T_{\mathrm{bst}} =& \frac{L_{\mathrm{RTS}} + L_{\mathrm{CTS}} + L_{\mathrm{DATA}} + L_{\mathrm{bst}} + L_{\mathrm{ACK}}}{k} \\ &+ 3 \times \mathrm{SIFS} + (N_{\mathrm{bst}} - 1) \times \mathrm{PIFS}.\end{aligned} \tag{3}$$

If the maximum tolerance for appropriate fairness and synchronization are T_f and T_s, respectively, we get

$$T_{\max} = \min(T_f, T_s). \tag{4}$$

If we substitute T_{bst} in (3) with $T_{\max}$, then the calculated N_{bst} is the maximum packet number allowance in a burst transmission, therefore $N_{\max}$ can be calculated by solving (3) and (4)

$$\begin{aligned}N_{\max} =& [k \times \min(T_f, T_s) - L_{\mathrm{RTS}} - L_{\mathrm{CTS}} - L_{\mathrm{ACK}} \\ &- 3k \times \mathrm{SIFS} + k \times \mathrm{PIFS}]/(L_{\mathrm{DATA}} + k \times \mathrm{PIFS}).\end{aligned} \tag{5}$$

Before burst transmission, a given sensor node firstly checks current packet number N_{cur}. In the buffer queue, if $N_{\mathrm{cur}} > N_{\max}$, N_{bst} is set to $N_{\max}$, while if $N_{\mathrm{cur}} < N_{\max}$, N_{bst} is set to N_{cur}.

By using burst transmissions, our protocol can not only reduce latency but also save energy. We used an RTS/CTS/ACK control packet series for burst transmissions, so $(N_{\mathrm{bst}} - 1) \times (\mathrm{RTS} + \mathrm{CTS} + \mathrm{ACK})$ control packets can be reduced, thus saving energy spent on delivering control packets.

In error-prone channels, when packet corruption is detected by a receiver in burst transmissions, the receiver does not notify the sender and continues to send all the remaining packets, failing to startup retransmission immediately. After all the data packets in a burst are sent out, the receiver uses a selective ACK scheme acknowledgings the received packets only. The sender then knows which packets are lost in the current burst transmission and schedules these packets at the front of the buffer queue, retransmitting them in the next burst transmission.

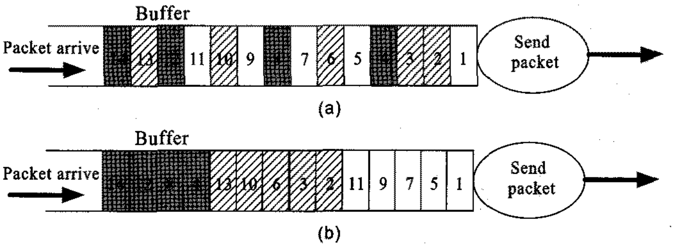


Fig. 5. Packets queue reordering: (a) Before reordering and (b) after reordering.

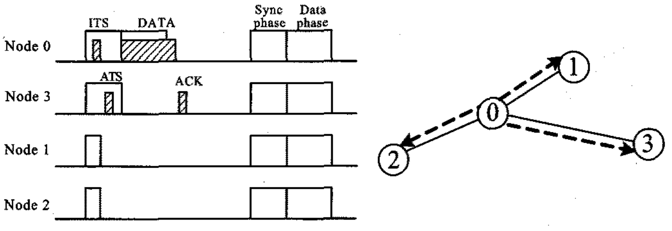


Fig. 6. Selective wake-up schedule.

If current sensor nodes have more than one next-hop node, the packets in the buffer queue are rearranged so that all the packets in each burst transmission contain the same next-hop address, thereby reducing retransmissions. This queue reordering method is illustrated in Fig. 5. Sensor nodes check the destination address of each packet form the bottom to the top of the queue (i.e., from packet 1 to packet 14). The nodes then select the first packet series with the same destination address and arrange these packets according to their original sequence in the queue (1,5,7,9,10). They then select the remaining packet series in the same manner. Since packet 1 is located ahead of packet 2 in the original queue, the burst packet series containing packet 1 will go ahead of the series contain packet 2.

This queue reordering method may introduce some difficulties. Firstly, fairness is affected, since one burst transmission may take a long time, meaning adjacent nodes cannot communicate properly. Secondly, there needs to be some CPU execution time to do packet reordering works. However, in most wireless sensor network applications, sensor nodes usually collaborate when completing tasks, so fairness is a less critical issue compared to those caused by energy or latency.

C. Selective Wake-up Schedule

VLA-MAC uses a selective wake-up schedule to remove unnecessary active periods. First, the sensor nodes estimate current traffic load L_k, and if L_k is lower than a threshold β, the selective wake-up schedule takes effect. The traffic load of one packet arriving in a cycle is L_0, and represents a base traffic load value. If the traffic load of a sensor node is lower than L_0, then traffic load is considered low and selective wakeup needs to take effect. We set $\beta = 2 \times L_0$ to ensure a sufficient threshold. Sensor nodes get the next-hop address from fields contained in the current data packet. They then construct a small invite to send (ITS) packet containing the address of the next-hop node and transmit it in sync phase using a carrier sense.

Fig. 6 shows the selective wake-up schedule. Here node 0 has

```
if(traffic load<β &&queue length== 0 &&txdata ==1)
    send ITS using carrier sense
    if (ATS recieved)
        send DATA packet in data phase
        receive ACK packet
    else if(collision detected&&in sync phase)
        use normal schedule in rest time
    else if (no ATS received)
        go to sleep immediately
    end if
else if (traffic load< β&&queue length==0 &&txdata ==0)
    if(ITS received)
        if (current node =destination)
            send ATS packet
            receive DATA packet and reply ACK
        else
            go to sleep immediately
        end if
    else if (cycle elapsed)
        wakeup use normal schedule
    else if (collision detected)
        use normal schedule in rest time
        send RTS use carrier sense in data phase
    end if
end if
```

Fig. 7. Pseudo-code description of selective wake-up schedule.

a packet which needs to be sent to its next-hop node 3 in the current cycle, so it firstly broadcasts an ITS in sync phase to its neighboring nodes. After receiving the ITS, node 3 checks the address field in the ITS to ensure it has the correct destination node, and then replies by sending an ATS to node 0. Meanwhile, nodes 1 and 2, understanding they are not the destination node responsible for receiveing the ITS, update their NAV and go to sleep early to save energy. At the beginning of the data phase, node 0 sends the DATA packet to node 3. After receiving the DATA packet, node 3 replies by sending an ACK to node 0 to confirm the current transmission. The current packet is thus delivered between node 0 and node 3 successfully. Since nodes 1 and 2 are already in a sleep state during the data phase, the transmission between node 0 and node 3 is unlikely to be interrupted.

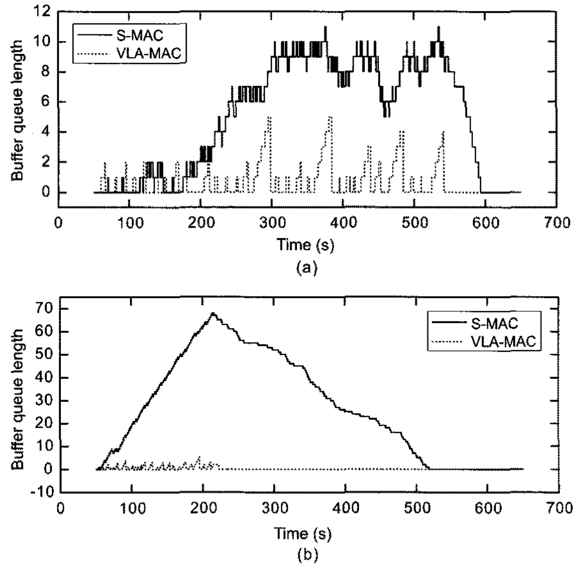
In the case of error prone channels, an ITS may encounter a transmission error resulting in the next-hop node not receiving the ITS correctly. This may result in increased latency since sensor nodes will attempt to resend the ITS transmission in the next cycle. If transmission errors occur frequently, unnecessary sleep action leads to a long latency. To eliminate such problems, VLA-MAC also sets a threshold θ. If a sensor node experiences θ cycles and does not receive an ITS correctly, it will wake up and use the normal schedule to listen to possible arriving packets to avoid long latency. The threshold θ is decided by consideration of latency and energy conservation tradeoffs. A representative value of 8 is effective.

In traditional approaches, once a sender transmits an ITS and encounters a collision, the next-hop nodes cannot get the address information from the ITS and will go to sleep immediately. This increases latency since the packet cannot be sent out in this cycle. In our design, whenever packet collision is detected by the receiver in sync phase, the sensor nodes stay in the awake state during the data phase and can listen for possible arriving packets. In the case of the sender, if it detects a collision in sync phase while it has a packet to send, it does not cancel the current carrier sense timer and does not go to sleep. It then adopts a normal schedule in data phase and sends a packet in RTS/CTS/DATA/ACK style through carrier sense. Latency can thus be reduced effectively since sensor nodes do not need to make another attempt at data transmission in the next cycle. The pseudo-code description of the selective wake-up schedule is illustrated in Fig. 7.

Table 1. Main simulation parameters.

Packet head	5 bytes	RTS, CTS, ACK	10 bytes
Packet size	512 bytes	Contend window	64
Transmit power	24.75 mw	Duty-cycle	0.1
Idle power	13.5 mw	Cycle length	1433 ms
Receiver power	13.5 mw	$N_{\max}$	8
Sleep power	0.015 mw	α	0.9
β	0.08	θ	8

Fig. 8. Multi-hop chain.



(a)

(b)

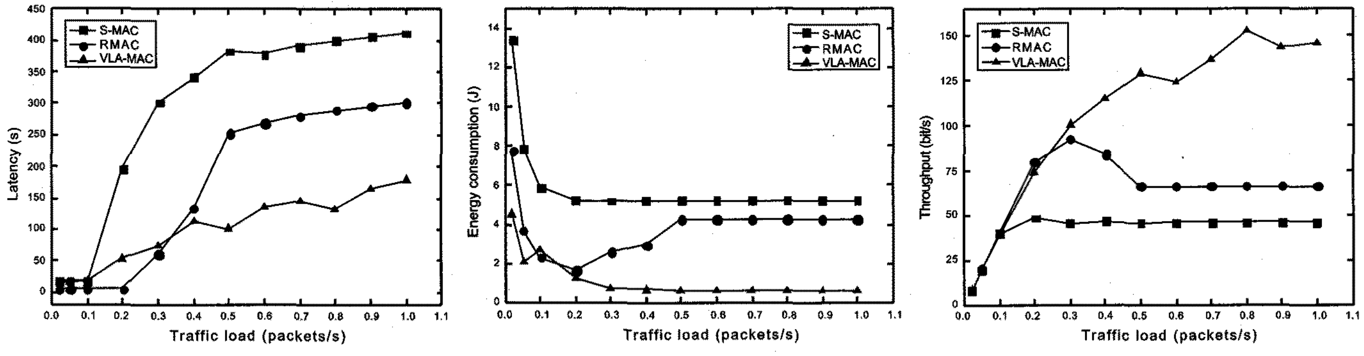
Fig. 9. Buffer queue length: (a) Traffic load= 0.2 packets/s and (b) traffic load= 0.6 packets/s.

In our protocol design, if a sensor node detects an error packet in sync phase, it then uses the normal schedule and does not remove the remaining active period in the current cycle. Sensor nodes use a relatively short NAV if such a packet error is detected, enabling them to perform normal transmissions in the data phase and reduce latency.

IV. SIMULATION RESULTS

In this section, we present extensive simulations to evaluate the performance of VLA-MAC in NS-2 [15] with CMU wireless extension. The main simulation parameters are summarized in Table 1. In the simulations, power in the transmitting, receiving, idle, of sleep state is referred to as TR1000 [16]. According to the default setting of NS-2, the transmission range of the sensor node is 250 m and the carrier sense range is 550 m.

We compared the metrics of energy efficiency, latency, and throughput of our protocol against S-MAC and RMAC. We did



(a) (b) (c)

Fig. 10. Performance in multi-hop chain topology: (a) Latency, (b) energy consumption, and (c) throughput.

not consider adaptive listening in S-MAC since according to [4], the latency of adaptive listening is half of the basic S-MAC, and consumes much more energy than the basic S-MAC. In our simulations, energy consumption is the energy required to deliver a certain number of packets from the source to the sink. Latency is the average delay in delivering a packet. Throughput is the total bits received by a sink node in a certain time. In our simulations, we set up three typical simulation topologies: Multi-hop chain topology, data gathering topology, and large-scale realistic topology.

A. Multi-Hop Chain Topology

We firstly set up a 10 node multi-hop chain topology for evaluating performance of our protocol. The distance between adjacent nodes is 200 m, the possible of which are illustrated in Fig. 8. A constant bit rate (CBR) data flow, which is based on a user datagram protocol (UDP) agent, is attached on source node 0, while node 9 is a sink node. Packets are sent from node 0 to node 9 in a multi-hop style. The distance between adjacent nodes is 200 m. Nodes in our simulation use a buffered size of 100 packets.

We first measured the queue length of sensor node 0 and studied the buffer accumulation alleviation ability of VLA-MAC. The CBR flow starts at 50 s and stops at 650 s. Fig. 9 compares the measured buffer queue length of VLA-MAC and S-MAC. When traffic load is equivalent to 0.2 packets/s, queue length of S-MAC increases markedly while VLA-MAC remains low. When traffic load increases to 0.6 packets/s, the queue length of VLA-MAC does not increase significantly, while the queue length of S-MAC does. When under heavy traffic load, multi-packets arrive in a cycle resulting in packets that cannot be sent at the appropriate time, leading to serious buffer accumulation problems. However, the queue length of VLA-MAC maintains a relatively low level during the entire simulation, since VLA-MAC measures buffer queue length before transmission. As soon as packet accumulation is detected, sensor nodes send multi-packets continually to alleviate packet accumulation. In addition, when traffic load increases, packet accumulation is brought forward and less time is required to send out packets.

We then studied the performance of latency, energy consumption and throughput using different protocols. The traffic load of CBR flow varied from 0.02 to 1 packets/s, and 100 packets were sent from a source to a sink. Fig. 10(a) shows the latency of different protocols. When traffic load increases, latency of all the protocols also increase. When traffic exceeds 0.3 packets/s, VLA-MAC latency readings remained at approximately 70% and 50% of those recorded by S-MAC and RMAC, respectively. During low traffic load, VLA-MAC also recorded a lower latency compared to S-MAC, while R-MAC achieved the lowest latency. During high load conditions, the accumulation of packets in the buffer is the main cause for the increase in the latency. S-MAC can not resolve this problem since only one packet is sent in a transmission. RMAC adopted a pipeline delivery style to deliver packets quickly when no packet accumulation occurs, while our protocol adopted a burst transmission scheme to send packets quickly and therefore reduce latency.

Fig. 10(b) shows the average energy consumption of the 10 nodes. As traffic increases, energy consumption decreases in S-MAC and VLA-MAC, but not in R-MAC. During low traffic load, the packet arrival interval is larger than during high traffic load. Therefore, when delivering 100 packets to the sink, it spends more time under low traffic load than high traffic load. The energy spent on idle listening during low traffic load is therefore larger than during high traffic load. Furthermore, the same amount of energy is required to send any similar number of packets, therefore energy consumption during higher traffic load is less than that during low traffic load. This is supported by our results showing that VLA-MAC achieves lower energy consumption than other protocols. RMAC cannot manage packet accumulation well, and introduces a large delay, resulting in more energy consumption. Fig. 10(c) shows that in high traffic load, throughput of VLA-MAC is nearly two times larger than S-MAC and three times larger than RMAC. During very low traffic load, all the protocols achieve similar throughput since no packet accumulation occurs and the time spent on packet delivery is short.

B. Data Gathering Topology

In this subsection, we further evaluate the performance of VLA-MAC under data gathering topology. Node positions are illustrated in Fig. 11. Nodes 0, 1, 2, and 3 are sources, and each node is attached to a CBR flow based on a UDP connection. Data flows are converged along a transmission path so that the traffic loads of sensor nodes near the sink are larger than sensor

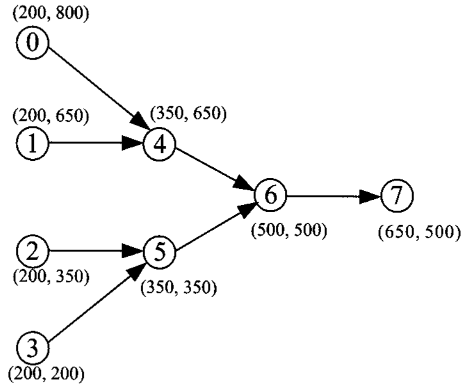


Fig. 11. Data gathering tree topology.

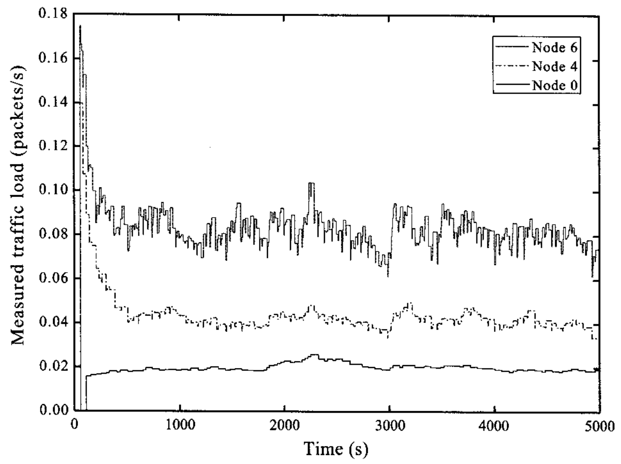


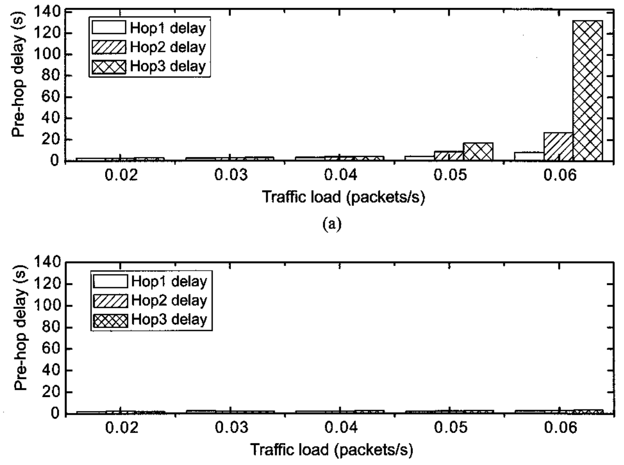
Fig. 12. Measured traffic load.

nodes far from the sink. Each CBR flow at the source nodes start at 50, 52, 54, and 56 s, respectively. Each source node ultimately sends 100 packets to sink node 7, so there are 400 packets sent to the network in total.

We first tested our traffic load estimation scheme, setting the traffic load of each flow to 0.02 packets/s, starting CBR traffic at 50 s and stopping it at 500 s. We then measured the traffic load at nodes 0, 4, and 6 continuously during the simulation. Fig. 12 shows the measured traffic load at node 0 was 0.02 packets/s, which is the same value as we initially set. The measured traffic load of node 4 reached 0.04 packets/s, which is almost twice that of the previous hop node, since two flows converge at node 4. Furthermore, the measured traffic load of node 6 received almost 0.08 packets/s, which was nearly four times that of node 0. This is because there are almost four flows converging at node 6. The measured traffic load of each node is accurate.

We then measured the per-hop delay along the data-gathering tree and studied the factors influencing latency. The traffic load on each source varied from 0.02 0.06 packets/s in our simulation. We defined hop 1, hop 2, and hop 3 to be the transmission between nodes 0 and 4, nodes 4 and 6, and nodes 6 and 7, respectively. We then measured the average per-hop delay of all 100 packets.

Fig. 13 shows the measured per hop delay. As the traffic load increased, the delay of each hop also increased. It is apparent the delay of hop 3 increased markedly with traffic load. The delay increase between hop 3 was greater than hop 2, which in turn was greater than hop 1. It is clear the bottleneck of long latency in data gathering occurs in the later hops. This occurs in data gathering tree topology, as packets converge along the data flow, and packet accumulation problems are more serious in later hops than in earlier hops. Per-hop delay in VLA-MAC remains low under different traffic loads. Unlike S-MAC, the delay of hop 3 in VLA-MAC does not rise above the delay in hop 1. Under high traffic load each hop delay can remain low since VLA-MAC performs burst transmissions based on local decisions, so packets in each hop can be sent quickly to reduce delay.



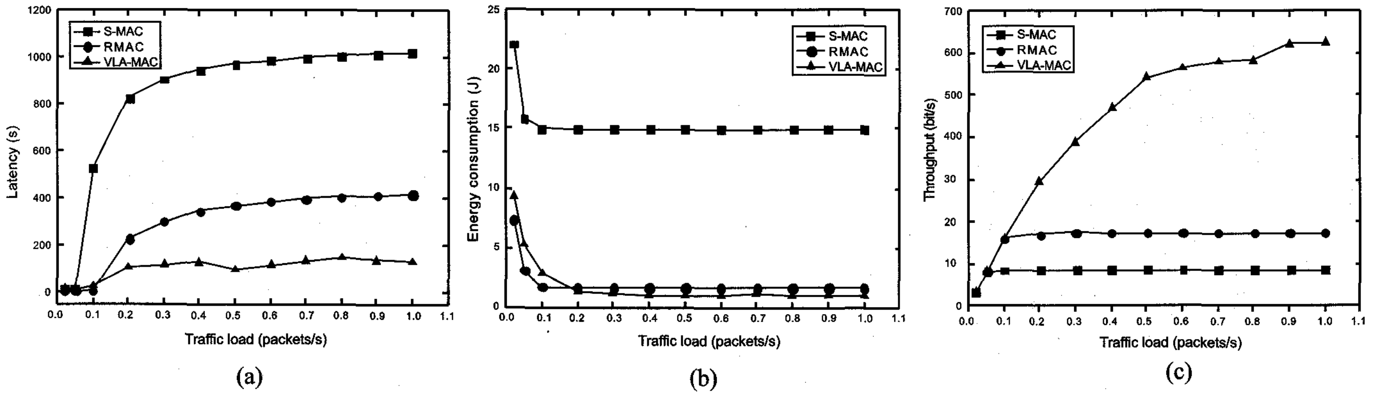
(a)

(b)

Fig. 13. Per-hop delay of (a) S-MAC and (b) VLA-MAC in data gathering topology.

We then compared the performance of different protocols under variable load conditions. The traffic load on each source varied from 0.02-1 packets/s. Fig. 14(a) shows the average packet latency of all 400 packets. With traffic load increases, latency of S-MAC increased steeply and displayed a high value throughout, while RMAC exhibited a relatively low latency during the increasing load conditions. VLA-MAC displayed the lowest latency because in data gathering topology, packets accumulate in the later hop near the sink, and when the traffic is heavy, packets accumulating in the buffer of the node near the sink are the main cause of latency increase. S-MAC does not resolve this problem effectively since only one packet is sent in a transmission. Our protocol is able to maintain low latency as it adopts a burst transmission scheme, which can send packets quickly.

Energy consumption is presented in Fig. 14(b). When traffic load increased, energy consumption of all the protocols firstly declined and then maintained stability. This is due to the shorter time required to deliver packets during heavy traffic load and the resulting reduction in time spent on idle listening. Once traffic load increases and reaches the networks saturation point, it requires almost the same time to deliver all the packets. It is also clear that VLA-MAC reduces to almost 1/4 the energy of RMAC, since it can send out packets quickly, thereby reducing the energy consumed during idle listening. It is also evident that during low traffic load, VLA-MAC maintains lower energy consumption than S-MAC as the select wakeup scheme has taken effect reducing unnecessary energy consumption.



(a) (b) (c)

Fig. 14. Performance in data gathering topology: (a) Latency (b) energy consumption, and (c) throughput.

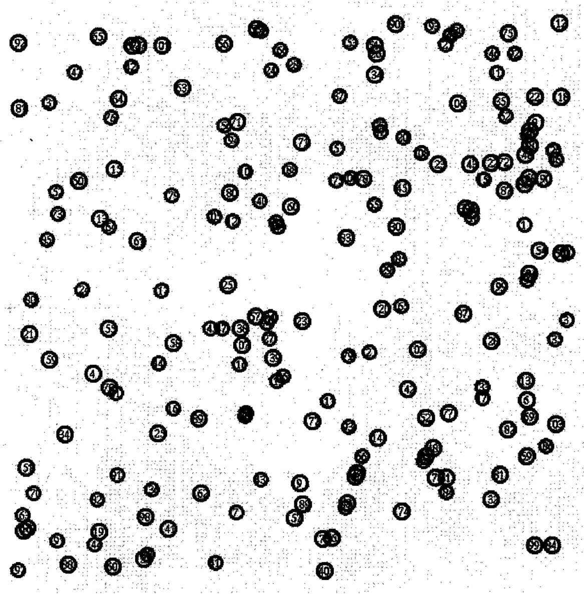


Fig. 15. Large-scale realistic topology.

As illustrated in Fig. 14(c) achieves the highest throughput, and is almost two times higher than RMAC and four times higher than S-MAC. This is because VLA-MAC is more efficient as it can send multi-packets in a burst transmission.

C. Large Scale Realistic Topology

In this subsection, we further evaluate the performance of VLA-MAC under more complicated large-scale realistic topology, as shown in Fig. 15. Two hundred nodes are randomly distributed in a 2000 m×2000 m square area. The sink node is located at the top right corner. Twenty source nodes are randomly selected from all 200 nodes and each is attached to a CBR flow with variable traffic load in run time. The traffic load on each source varies from 0.021 packets/s. All the source nodes start packet transmission at the same time, and each generates 10 packets during simulation, so there are a total of 200 packets sent to the networks. In this topology, a statically chosen shortest routing path is used.

Fig. 16(a) shows the measured latency under different traffic loads. Throughout the increasing traffic load, S-MAC maintained the highest latency, which was almost 20 times that of VLA-MAC. The latency of RMAC was significantly lower than that of SMAC. VLA-MAC achieved the lowest latency: Almost 30% of RMAC. Packet accumulation is a more serious problem for large realistic topology than for data gathering topology. The links near the sink create bottlenecks for the whole network, which is then more likely to enter a state of saturation. S-MAC uses a normal listen/sleep schedule and cannot transmit quickly. RMAC adopts a pipeline mode to transmit packets so that during a cycle packets can be delivered in several hops, but can only send one packet in a pipeline operation. VLA-MAC can send several packets in a cycle, which alleviates the packet accumulation problem.

The energy consumption values shown in Fig. 16(b) show that S-MAC consumed the most energy, while RMAC and VLA-MAC both consumed significantly less. Furthermore, VLA-MAC used only 50% of the energy consumed by RMAC, for the reasons already explained. During low traffic load, energy consumption of VLA-MAC is also reduced since in a large-scale network, each sensor node can remove unnecessary wakeup action to save energy.

Throughput of the protocols is shown in Fig. 16(c). Clearly, the throughput of VLA-MAC was higher than both RMAC and S-MAC. This is because when delivering a certain number of packets, S-MAC takes the longest time to deliver all the packets due to its listen/sleep schedule. RMAC, although it also transmits a packet in a cycle, uses a pipeline style that can deliver packets using several hops in a cycle, thereby further reducing transmission time. VLA-MAC is the fastest since it can adopt a burst transmission to send more packets in a cycle.

V. CONCLUSIONS

In this paper, we presented an efficient adaptive MAC protocol for variable-traffic-load wireless sensor networks. Sending multiple packets in bursts under high-load conditions causes a significant reduction in latency. Further, energy can also be saved by reducing packet overhead. Under a low traffic load condition, by exchanging ITS with ATS packets in sync phase, uncorrelated sensor nodes in the network can reduce unnecessary wake-up action and save energy. Our protocol does not need to adjust the duty-cycle online; therefore, its implementation is straightforward, and the design does not cause synchronization

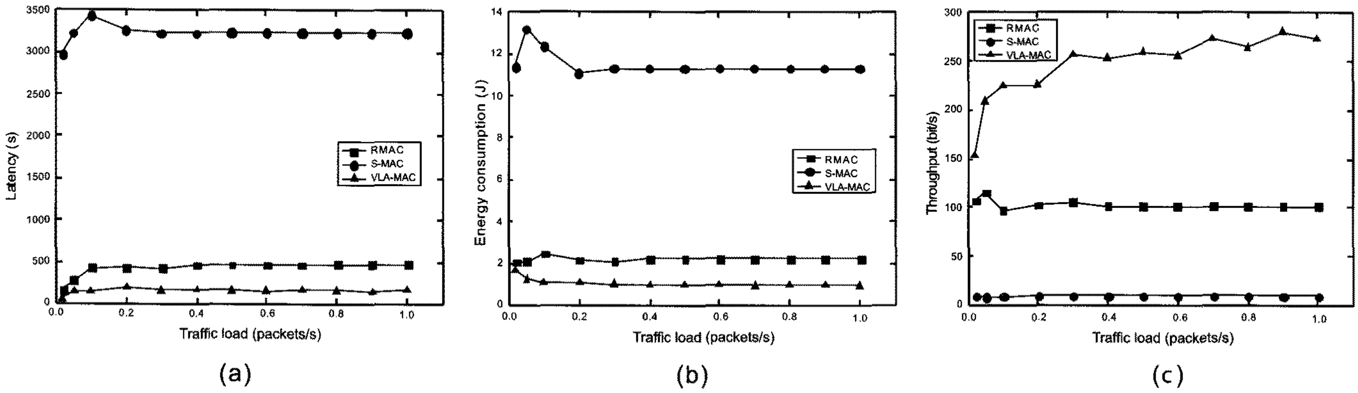


Fig. 16. Performance in realistic topology: (a) Latency, (b) energy consumption, and (c) throughput.

problems. Through extensive simulation based on NS-2, we validated the performance of our protocol design and compared it with S-MAC. The results show that our protocol significantly reduces latency and is clearly more energy efficient than other traditional protocols.

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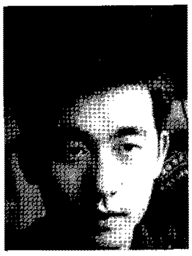

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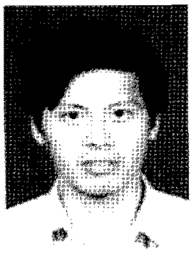

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