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# A novel efficient power-saving MAC protocol for multi-hop MANETs

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## SUMMARY

Following recent advances in the performance of *ad hoc* networks, the limited life of batteries in mobile devices poses a bottleneck in their development. Consequently, how to minimize power consumption in the Medium Access Control (MAC) layer of *ad hoc* networks is an essential issue. The power-saving mode (PSM) of IEEE 802.11 involves the Timing Synchronization Function to reduce power consumption for single-hop mobile *ad hoc* networks (MANETs). However, the IEEE 802.11 PSM is known to result in unnecessary energy consumption as well as the problems of overheating and back-off time delay. Hence, this study presents an efficient power-saving MAC protocol, called *p*-MANET, based on a Multi-hop Time Synchronization Protocol, which involves a hibernation mechanism, a beacon inhibition mechanism, and a low-latency next-hop selection mechanism for general-purpose multi-hop MANETs. The main purposes of the *p*-MANET protocol are to reduce significantly the power consumption and the transmission latency. In the hibernation mechanism, each *p*-MANET node needs only to wake up during one out of every $N$ beacon interval, where $N$ is the number of beacon intervals in a cycle. Thus, efficient power consumption is achieved. Furthermore, a beacon inhibition mechanism is proposed to prevent the beacon storm problem that is caused by synchronization and neighbor discovery messages. Finally, the low-latency next-hop selection mechanism is designed to yield low transmission latency. Each *p*-MANET node is aware of the active beacon intervals of its neighbors by using a hash function, such that it can easily forward packets to a neighbor in active mode or with the least remaining time to wake up. As a consequence, upper-layer routing protocols can cooperate with *p*-MANET to select the next-hop neighbor with the best forwarding delay. To verify the proposed design and demonstrate the favorable performance of the proposed *p*-MANET, we present the theoretical analysis related to *p*-MANET and also perform experimental simulations. The numerical results show that *p*-MANET reduces power consumption and routing latency and performs well in extending lifetime with a small neighbor discovery time. Copyright © 2011 John Wiley & Sons, Ltd.

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KEY WORDS: IEEE 802.11; mobile *ad hoc* networks (MANETs); power saving protocols; MAC layer

## 1. INTRODUCTION

Following recent improvements in the performance of wireless communication systems, mobile *ad hoc* networks (MANETs) [1] have become increasingly important in increasingly wide range of applications, such as battlefields and other military environments, disaster areas, and outdoor activities. A MANET is a multi-hop wireless network that is formed dynamically from an accumulation of mobile nodes without the assistance of a centralized coordinator. As the radio propagation range is limited, each mobile node has only limited information, such as its own ID and the Medium Access Control (MAC) address of its one-hop neighbors. Therefore, if two nodes are not within the radio propagation range, a multi-hop, via one or more intermediate nodes, is required to forward packets.

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The forward function of each intermediate node consumes time and resources, such as power and bandwidth. However, a mobile node has limited power. This study addresses the maximization of the lifetime of mobile nodes through various mechanisms.

The power consumption of a battery in a mobile node must be minimized to maximize its lifetime [2, 3]; otherwise, the battery may quickly run out of power, making the mobile node useless. The operating states of a network interface can be categorized into transmit, receive, idle, and sleep states, and the estimated power consumption of each state is as presented in Table I. An interface in the sleep state can neither transmit nor receive any packets, and thus this state consumes the lowest power. To be able to transmit and receive packets, an interface must be woken up. A mobile node that is awake, but neither transmitting nor receiving data, is said to be idle. A node consumes the most power when it is in the awake state. Therefore, the proposed power-efficient protocol depends on mobile nodes' staying in the sleep state most of the time, unless data have to be transmitted.

The reduction of power consumption by MANETs has been studied widely. Existing power-saving MAC protocols can be classified into two categories—synchronous wake up approaches [4–8] and asynchronous wake up approaches [10–15]. In synchronous wake up approaches, all nodes must execute a clock synchronization mechanism [4, 16–20]. Asynchronous wake up approaches require no such synchronization mechanism. However, the neighbor discovery time is the most important issue in asynchronous wake up approaches. They must adjust the overlap of a node's wake up time with that of its neighbors, resulting in increased power consumption and long transmission delay. Thus, this study focuses on the synchronous wake up approach.

This study proposes a synchronous MAC layer power-saving protocol, called $p$-MANET. The proposed $p$-MANET employs Multi-hop Time Synchronization Protocol (MTSP) [20] as its underlying synchronization protocol. Our design can support any routing protocols or applications. In $p$-MANET, the three mechanisms that are utilized to reduce power consumption and transmission latency are hibernation, beacon inhibition, and low-latency routing selection. As a node in active mode can waste energy on useless tasks, such as idle listening, collision, overhearing, and control mechanism, the hibernation mechanism eliminates the power consumption that is associated with these tasks. In particular, a $p$-MANET node can be in listen mode or power-saving mode (PSM). In listen mode, a node wakes up and is able to receive packets. When a node enters PS mode, it sleeps most of the rest of the time, except when it is transmitting data to neighboring nodes or sending beacon messages periodically. In this mechanism, each node is in listen mode for one interval during a cycle of $N$ intervals. One of the most important features of the hibernation mechanism is that each node determines when to enter the listen mode based on a global hash function. As each node periodically sends a beacon in the beacon window (BW) to synchronize and discover neighbors, the beacon inhibition mechanism is developed to solve the beacon storm problem. Furthermore, a low-latency routing selection mechanism is proposed to exploit heuristic strategies to select the next-hop neighbor node efficiently in the transmission of packets. For example, a favorable next-hop candidate may be a neighbor that will wake up soon.

To verify the proposed design and demonstrate the favorable performance of the proposed $p$-MANET, we present the theoretical analysis related to $p$-MANET concerning in terms of the average awake time and average delay time. In experimental simulations, the performance of $p$-MANET is evaluated using the metrics of survival ratio, neighbor discovery time and transmission latency, by simulation. The simulation results demonstrate that $p$-MANET uses approximately 70% less energy than the quorum-based protocol [11]. The experimental results also show that the average neighbor discovery time of $p$-MANET is substantially less than that of the quorum-based protocol.

Table I. Power consumption of network interface (Cisco AIR-PCM350, Cisco Systems, Inc., Milpitas, CA).

| Status | Transmit | Receive | Idle | Sleep |
|---|---|---|---|---|
| Power consumption (W) | 1.875 | 1.3 | 1.08 | 0.045 |

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The remainder of this paper is organized as follows. Section 2 explicates preliminaries. Section 3 discusses the main design principles of $p$-MANET. Section 4 presents the theoretical analysis of $p$-MANET. Section 5 presents the performance evaluation results. Section 6 draws conclusions and makes recommendations for future research.

## 2. PRELIMINARIES

Various power-saving protocols for IEEE 802.11 wireless local area network have recently been proposed. This section briefly reviews several power-saving protocols [4–15] and discusses some of the problems associated with MANETs, as the synchronous power-saving approaches, which require an effective time synchronization mechanism, is considered. Section 2.2 also reviews numerous time synchronization mechanisms [4, 16–20].

### 2.1. Reviews of power-saving protocols

*2.1.1. Synchronous wake up approaches.* The most well-known synchronous wake up power-saving protocol is the IEEE 802.11 standard [4], which was originally designed for single-hop *ad hoc* networks. As shown in Figure 1, time is divided into beacon intervals. In the PSM of the IEEE 802.11 standard, all nodes are synchronized by transmitting beacon frames to one-hop neighbors at the beginning of the beacon interval. After the beacon frame has been sent, the node sends an *ad hoc* Traffic Indication Map (ATIM) frame to inform other nodes that it has packets that are waiting to be transmitted during the ATIM window. Upon receiving an ATIM-ACK frame from the destination node, a node obtains the right of transmission and begins to transmit data immediately after the ATIM window ends. Both sender and destination nodes are awake during the transmission period. Otherwise, at the end of ATIM window, a node enters the power-saving state.

IEEE 802.11 PSM has been extended to multi-hop MANETs [5], to activate paths, minimize delay, and conserve energy. However, the proposed synchronization strategy, routing strategy, and power management capability depend on extra support from MAC layer. Additionally, the potential problem of network partitioning has not been addressed.

Span [6] is based on the notion of a dominating set and extends the sleep time of mobile hosts to reduce power consumption. Span adaptively elects coordinators to generate a connected domination set; they are kept awake at all times to perform low-latency multi-hop routing. Other non-coordinators go through periodic cycles of sleep and wakefulness and periodically check whether they should wake up and become coordinators. Although Span guarantees efficient energy consumption and low delay latency in dense networks, it has two limitations. One is that coordinators must remain active at all times, broadcasting HELLO messages to maintain the backbone, increasing the overhead. The other is its synchronization overhead.

Special-purpose methods for reducing power consumption of MANETs have been proposed [7, 8]. A node can power down during its natural silent periods [7]: when a node does not expect to transmit, receive, or relay packets, it can power off its network interface. Traffic aware PSM (TA-PSM) [8] also achieves good performance with a light traffic load. TA-PSM allows the node directly to enter the doze state when it does not need to transmit or receive packets, even if a beacon or ATIM frame has to be sent. Instead of entering the idle state of IEEE 802.11 PSM, the node enters a doze state to save more power. However, such approaches depend on the monitoring of traffic at each node to guarantee transmission throughput and low transmission latency. Hence, these approaches may be not suitable for heavy traffic scenarios.

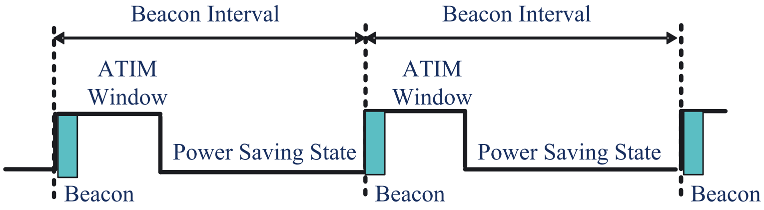

Figure 1. Power-saving mode of IEEE 802.11 standard.

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The neighborhood aware approach has been proposed in [8, 9]. Power-saving mechanisms (NA-PSM) [8] and the neighborhood and traffic aware power saving mechanism (NTA-PSM) [9] were proposed to reduce the number of exchanged announcement frames to increase throughput and reduce both power consumption and transmission delay. A NA-PSM node knows the state of neighbors and uses few ATIM announcement frames to increase bandwidth and carry more packets. However, the NA-PSM node has to stay in active mode throughout the beacon interval, even when the transmission or reception is complete. NTA-PSM is a variant of NA-PSM and allows each node to enter sleep mode when the transmission or reception is complete.

*2.1.2. Asynchronous wake up approaches.* Several asynchronous wake up approaches have been proposed [10–15]. Nodes in the network in an asynchronous wake up approach can independently enter active states and power save states without clock synchronization. As each node has no idea of the wake up time of its neighboring nodes, a live routing path to the destination node is not always available. To improve the availability of the routing path, we must design carefully both the power-saving mechanism and the neighbor discovery mechanism of the asynchronous wake up approach. Consequently, the wake up times of a node and its neighbors must overlap until the transmission between two nodes has been completed.

Both the basic energy-conservation algorithm (BECA) and the adoptive fidelity energy-conservation algorithm (AFECA) [10] minimize the power consumption of transmitters during idle time while introducing latency into the system. In BECA, nodes are in one of the three states—active, listen, and sleep. Each node alternates between the sleep and listen states if its traffic is low. A node enters the active state when it receives or transmits a large number of packets and then enters the sleep state when it has been idle for a while. BECA also integrates power-saving and routing mechanisms: when establishing a routing path, only the nodes along the routing path remain in the active state; other nodes enter the idle or sleep state. The AFECA improves the performance of BECA by applying knowledge of node deployment density and increasing the sleep time when neighbor nodes are available. However, AFEAC has two weaknesses that make it less able to reduce power consumption. First, numerous broadcast messages are required to carry information about neighbors. Second, the use of AFEAC to establish and maintain routing paths introduces long latency because only a few nodes are in the active state to handle routing request and response packets.

The quorum-based asynchronous power-saving protocol [11–14] assigns to each node a cycle pattern that specifies the wake up/sleep schedule. Tseng *et al.* [11, 12] presented a quorum-based asynchronous power-saving protocol. The design of quorum-based protocols is based on the concept of a quorum, such that a node only transmits in $O(1/n)$ of the beacon intervals, reducing the power consumed for sending beacons. Accordingly, the quorum-based protocol solves the contention problem and improves the efficiency of power saving. This protocol guarantees that any two nodes have at least two entire BWs that are fully covered for some beacon intervals, using the quorums to identify the beacon intervals during which a host must wake up. However, efficient power saving by this approach requires many beacons to communicate with neighbors, potentially increasing the neighbor discovery overhead and the neighbor discovery time. Zheng *et al.* [13] also presented an asynchronous wake up mechanism that is highly scalable to large networks, in which the wake up node wakes up for an entire beacon interval. Hyper quorum system (HQS) [14] is a fully adaptive quorum-based asynchronous power-saving protocol. An HQS node can select an arbitrary cycle length that fulfills the requirements of an application, such as packet delay and power constraint.

Chao *et al.* [15] proposed a new quorum-based asynchronous power-saving protocol, including Quorum-Based Energy Conservation (QEC) and Adoptive QEC (AQEC) in single-hop MANETs. This protocol maximizes the sleep time potentially to exceed one beacon interval if few transmissions are required. Nodes are woken up by the traffic load, rather than periodically. This power-saving protocol thus not only conserves energy but also balances the delay latency. However, AQEC is designed for single-hop MANETs.

Kim [28] proposed three synchronous power management protocols, denoted as synchronous PFAI (SPFAI), efficient SPFAI (ESPFAI), and non-Multi-hop Traffic Indication Map (MTIM) SPFAI (NSPFAI) protocols for MANET. SPFAI is extended PFAI protocol that is an asynchronous approach to synchronization approach. ESPFAI provided MTIM management scheme to reduce transmission overhead. NSPFAI omitted MTIM-ACK sequence to reduce power consumption and protocol complexity. However, the performances of these protocols are not discussed in this paper.

### 2.2. *Time synchronization mechanism*

Time synchronization has received considerable interest [4, 16–20]. Time synchronization is the most important element of synchronous wake up power-saving protocols. However, most current protocols are for single-hop MANETs, such as the Timing Synchronization Function (TSF) [4], the Adaptive Timing Synchronization Procedure (ATSP) [16], and the Tiered ATSP (TATSP) [17]. The most well-known example is IEEE 802.11 TSF, in which all nodes are synchronized by transmitting a beacon, which includes a synchronization timestamp at the beginning of each beacon interval. Upon receiving a beacon, each node synchronizes its TSF timestamp to that of the received beacon if the latter is faster. However, IEEE 802.11 TSF may suffer from the 'beacon contention problem' of dense networks, which prevents the fastest node from transmitting its beacon successfully. Therefore, the network loses synchronization when the maximum clock skew exceeds 224 $\mu$s [18]. Moreover, these protocols for single-hop MANETs are not suited to multi-hop MANETs.

The extension of the synchronization protocol for multi-hop MANETs has not been widely addressed in the literature because of unexpected topological changes and the packet delay problem in large-scale networks. Sheu *et al.* [19] proposed a time synchronization scheme, called the Automatic Self-time-correcting Procedure (ASP), for multi-hop networks. In ASP, mobile nodes adjust their clocks in response to beacon information from neighbors. However, the convergence time of synchronization is too long, so the clocks may still lose synchronization.

In order to address the time synchronization problem in $p$-MANET, Chen *et al.* [20] recently presented the MTSP. The MTSP consists of BW and synchronization (SYN) Phase. The BW phase tackles the synchronization accuracy problem in high-density single-hop networks, whereas the SYN phase solves the time partition problem in multi-hop networks. In BW, as in [21], a faster node has a higher priority for sending beacons. Hence, many one-hop synchronization groups are formed, and the fastest node in each group is selected as the group leader node. The SYN phase synchronizes leader nodes, subsequently synchronizing nodes in their groups. Simulation results demonstrate that the average maximum clock skew of MTSP is always less than 50 $\mu$s, which is far less than the out-of-synchronization threshold of IEEE 802.11, 224 $\mu$s. As MTSP guarantees a very high synchronization accuracy and low synchronization overhead, it is adopted as the underlying time synchronization protocol in this work. In fact, any synchronization protocol can be used adopted herein, but it must be a multi-hop approach with high synchronization accuracy and low synchronization overhead. MTSP has these features and performs very well. Furthermore, no network partition problem arises in MTSP when the ratio of the transmission range of the synchronization packets to that of the beacon packets is three.

## 3. $p$-MANET PROTOCOL

This section presents a novel efficient power-saving protocol called $p$-MANET, similar to the protocol of PS mode in IEEE 802.11 but applicable to multi-hop MANETs. The basic system model and components of $p$-MANET, including the hibernation mechanism, the beacon inhibition mechanism, and the low-latency next-hop selection mechanism, are described in detail. The main goal of the design of $p$-MANET is to minimize power consumption, message overhead, and transmission latency in multi-hop MANETs. The hibernation mechanism assumes that all nodes can be synchronized by applying a global synchronization algorithm, such as MTSP [20] or other synchronization algorithms. Each node only enters listen mode once every $N$ intervals to avoid consuming power on unnecessary tasks, such as idle listening, collision, overhearing, and control mechanism. The beacon inhibition mechanism is developed to solve the beacon storm problem. The low-latency next-hop selection mechanism supports a heuristic strategy for efficiently selecting a next-hop neighbor node for forwarding packets.

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### *3.1. System model*

This subsection describes the system model of $p$-MANET. In $p$-MANET, time is divided into several periods, called beacon intervals. Figure 2 depicts a beacon interval structure of $p$-MANET protocol with three intervals. Each beacon interval consists of three windows, the BW, the MTIM window [11], and the data window (DW). Notably, the MTIM window serves a similar purpose to the ATIM window in IEEE 802.11. The power management mode of a node in $p$-MANET is listen or PSM. In listen mode, a node wakes up and can receive data. For most of the rest of the time, it sleeps, except when it is transmitting data. To synchronize the clock and to discover neighbors, a mobile node periodically sends a beacon to eliminate the drift time with neighbor nodes in each BW, regardless of whether it is in the listen or the sleep mode. Additionally, on the basis of the characteristics of wireless communication, each node is assumed to know the MAC addresses of it neighbors.

### *3.2. Hibernation mechanism*

A node in active mode can waste energy on useless tasks, such as idle listening, collision, overhearing, and control mechanism, and the hibernation mechanism eliminates the power consumption that is associated with these tasks. In Section 3.2.1, we describe the hibernation mechanism on how to avoid unnecessary listening time. Then, avoidance of collision and overhearing is discussed in Section 3.2.2.

*3.2.1. Listen/sleep schedule.* A novel mechanism by which a node to determine when to enter the listen node is proposed in $p$-MANET. To reduce power consumption, $N$ beacon intervals form a cycle, and each node enters the listen mode only once per cycle if it has no data to transmit. Each node uses its MAC address as the input to a pre-chosen global hash function, such as SHA-1 [30], to determine which beacon interval needs to enter the listen mode. All $p$-MANET nodes share the same hash function, and all next-hop nodes in the routing table of a mobile node are neighbors of the node. Therefore, a $p$-MANET node that wants to transmit a packet must first look up the proper next-hop node from the routing table. It then utilizes the global hash function to determine the beacon interval in which the next-hop node enters listen mode and sends the MTIM frame and the packet in that beacon interval. Consequently, the next-hop node can listen to the MTIM frame and receive the packet in the DW.

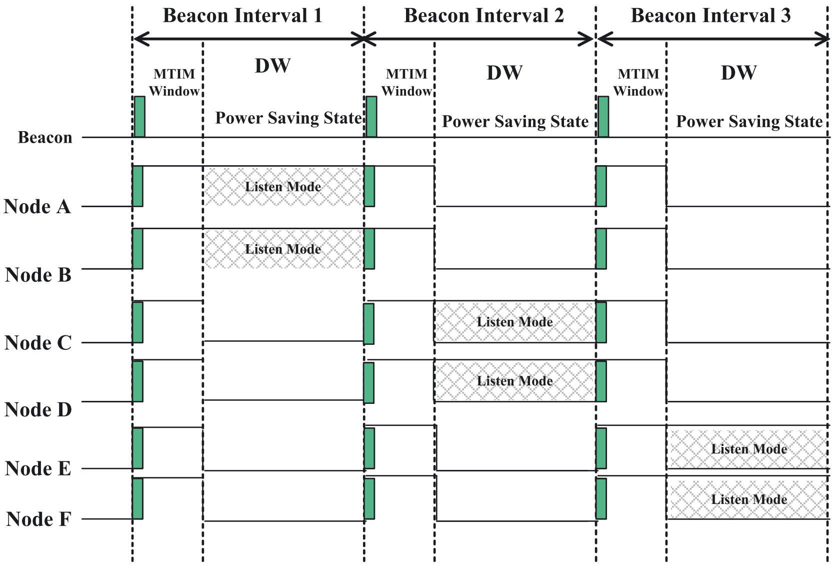

Figure 2. A structure of beacon interval of $p$-MANET with three intervals.

How do nodes learn about each other's existence and MAC addresses? In IEEE 802.11b, broadcasting hello message is always performed whereas data transmissions normally are sent. Many wireless MAC as in IEEE 802.11 need symmetric links in order to transfer data. Moreover, each mobile node in MANETs performs neighbors sensing by periodically broadcasting hello messages on all their interfaces. We assume that all neighbors have a symmetrical link with the originator of the hello and build a neighbor table. Thus, the hello messages contain the list of the neighbor nodes with its own ID and MAC address heard by the originator of the hellos. As a consequence, the neighbor discovery overhead is the basic cost of a node in MANETs, and each $p$-MANET node can construct its neighbor table without extra cost. We will discuss neighbor discovery overhead in Section 5. We can observe that it does not need to be considered in more details.

With the hash function, the proposed mechanism is much more efficient than the solution proposed elsewhere [5], in which each node must execute a schedule bookkeeping protocol to keep track of the schedules of its neighbors. Accordingly, our proposed mechanism can avoid unnecessary listening and offers the greatest power saving when $N$ is large. The number of beacon intervals can be increased to reduce the awake time and the power consumption of a node. As BW and MTIM are much smaller than DW, the percentage of time that a mobile node is awake approximates $1/N$ as $N$ becomes large, as shown in Figure 3. However, reducing the percentage awake time increases the transmission latency. Section 5 will discuss the trade-off between power consumption and transmission latency for the proposed mechanism.

Figure 4 depicts an example of the transmission of a packet. On the basis of the hash function, nodes $A$, $B$, and $C$ enter listen mode in beacon intervals 1, 2, and 3, respectively. If node $B$ wishes to transmit a data frame to node $C$, then it first determines the interval in which node $C$ will enter the listen mode, using the hash function. During the MTIM window of beacon interval 2, node $B$ sends an MTIM frame to inform node $C$ that a data frame is to be sent to it. Node $C$ replies by sending an ACK to node $B$. As node $A$ has no packet to send, it enters the sleep mode after the BW window of interval 2. Node $B$ enters the sleep mode after it receives the ACK from node $C$, which can also enter the sleep mode if all data indicated in the MTIM window have been received.

*3.2.2. Avoidance of collision and overhearing.* The MAC layer of IEEE 802.11 is based on a contention-based scheme, Carrier Sense Multiple Access with collision avoidance mechanism, denoted as CSMA/CA protocol, to solve the collision problem. A CSMA/CA protocol works as follows: a node senses whether the medium is idle, and if the medium is idle, then a node is allowed to transmit RTS. After the receiver obtains the RTS, it sends back the CTS. These RTS/CTS are used to avoid hidden and exposed terminal problem.

Avoidance of collision and overhearing in $p$-MANET is efficient in reducing power consumption. Our protocol exploits a similar collision avoidance mechanism, which involves both virtual and physical carriers and the RTS/CTS handshaking mechanism. In $p$-MANET, beacon messages

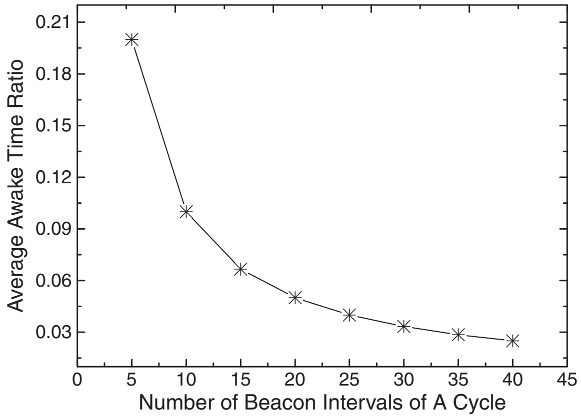

Figure 3. Relationship between average awake time ratio and number of beacon intervals.

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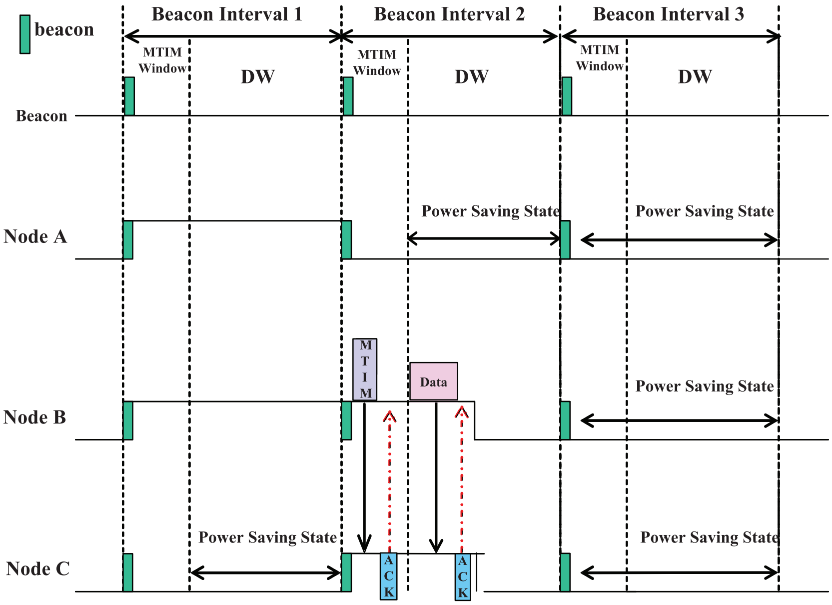

Figure 4. An example of transmission of packets.

are sent without RTC/CTS handshaking, whereas the MTIM and data frames are sent in a sequence of four operations, RTS/CTS/DATA/ACK, which are executed between the sender and the receiver to avoid overhearing. The Network Allocation Vector (NAV) concept in IEEE 802.11 is adopted and extended in $p$-MANET to avoid collision and save power. The NAV of IEEE 802.11 denotes the time remaining in an ongoing data transmission. The channel is regarded as busy if the NAV value is not zero. On the basis of the NAV, a mobile node in $p$-MANET can either stop sensing the physical transmission medium or enter sleep mode to save power if it is not corresponding to sender or receiver.

Figure 5 depicts an example of how a $p$-MANET node adopts the NAV. Consider the case, shown in Figure 5, in which nodes $A$ and $B$ want to send data packets simultaneously to node $C$. Recall that nodes $A$ and $B$ enter the listen mode in beacon interval 1 and node $C$ enters the listen mode in

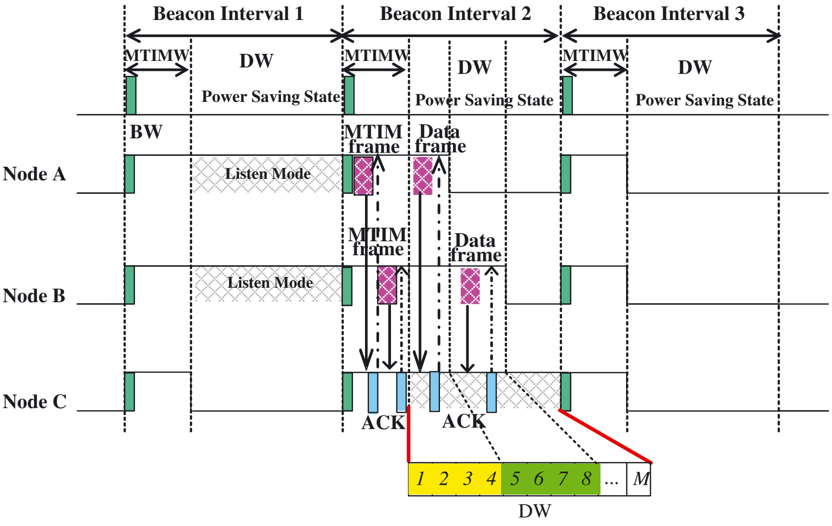

Figure 5. Scheduling of mobile node $C$ when NAV is used.

beacon interval 2. In Figure 5, nodes $A$ and $B$ send the MTIM frame to node $C$ during the MTIM window of beacon interval 2. Consequently, node $C$ may receive the MTIM frame from both nodes $A$ and $B$. The DW is divided into $M$ slots, which are utilized to schedule the transmission of packets by numerous nodes. Assume that node $C$ first receives the MTIM frame from node $A$. Node $C$ can schedule node $A$ to send a data frame in slots 1–4 of the DW in interval 2 and include this scheduling information in the ACK of the MTIM frame to node $A$. Node $C$ later receives the MTIM frame from node $B$, which is scheduled to send a data frame in slots 5–8. Similarly, node $B$ receives this scheduling information in the ACK from node $C$. During the DW, as other sender/receiver pairs may also be scheduled for transmission, nodes $A$ and $B$ must still use RTS/CTS to seize the channel before transmission. However, node $B$ can enter the sleep mode during the first four slots, as node $A$ is scheduled to transmit first. Node $A$ can enter the sleep mode after transmission. Other nodes can use the NAV of RTS/CTS to estimate the duration of to sleep before waking up to re-contend for the channel. Node $C$ can enter the sleep mode if it has no data to receive.

### *3.3. Beacon inhibition mechanism*

Beacon inhibition mechanism of $p$-MANET is designed for densely distributed MANETs. We explain the details of beacon inhibition mechanism as follows. In order to save energy, each node enters PS mode unless it wakes up in beacon interval. For example, in Figure 4, node A wakes up in beacon interval 1 and it switches to PS mode during beacon intervals 2 and 3. And if there are no packets to node A, it can enter PS mode after MTIM window. Moreover, nodes need to discover their neighbors and synchronize their clocks in MTIM window. In a dense MANET, the probability of nodes that wake up in the same beacon interval will be increased. It implies that the number of collisions should be increased, because the MTIM window applies the contention-based mechanism. The beacon inhibition mechanism is designed to reduce the number of collisions to improve the transmission efficiency of packets during the MTIM window. The main idea of beacon inhibition mechanism is that a mobile node emits a beacon message only if the total number of beacon messages that are received in the current BW is less than a threshold. We define a threshold as follows. A mobile node emits a beacon message only if the total number of beacon messages that are received in the current BW is less than a threshold. The threshold ($N_{\mathrm{bw}}$), given by Equation (1), can be estimated from the length of BW ($L_{\mathrm{bw}}$) and the time taken to send a beacon ($t$). For instance, if the BW is 4 ms, and sending a beacon takes 0.5 ms, then the threshold is 8. Thus, the main contribution of beacon inhibition mechanism is to reduce the number of collisions, especially in densely distributed MANETs.

$$N_{\mathrm{bw}} = \frac{L_{\mathrm{bw}}}{t} \tag{1}$$

Therefore, in the beacon inhibition mechanism, a $p$-MANET node counts the beacon messages received so far and stops sending beacons if the number exceeds the pre-defined threshold. Figure 6 presents a flowchart of the beacon inhibition mechanism.

### *3.4. Low-latency next-hop selection mechanism*

The proposed $p$-MANET is a foundational MAC layer protocol for general-purpose multi-hop MANETs, but provides a routing metric to enable routing protocols to choose the most efficient next-hop forwarding node. The routing path satisfies power-saving and delay requirements. $p$-MANET can support any routing protocol. However, transmission latency can be reduced if the adopted routing protocol exploits the power management strategy of $p$-MANET. Two conditions are needed to check if the delay constrains and time of entering listen mode are satisfied. The following neighbor selection strategy is proposed for the route discovery process of distance vector-based (table-driven) routing protocols and on-demand routing protocols.

Table-driven protocols, such as destination-sequenced distance vector [22], maintain a routing table in which each entry contains destination and next-hop information. When a source node wishes to send a data packet to a destination node, two or more neighboring nodes may be equally favorable for forwarding packets to a given destination. In this case, most routing protocols randomly

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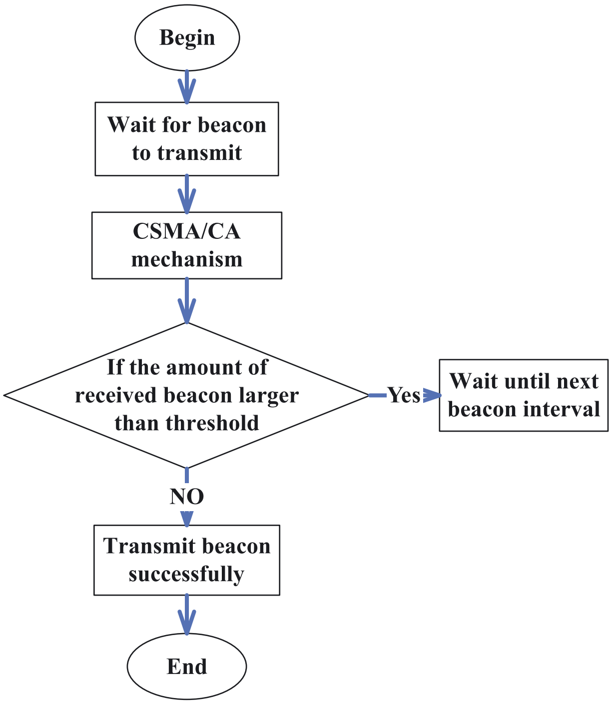

Figure 6. Flow chart of beacon inhibition mechanism.

select one neighboring node as the next hop. In the proposed $p$-MANET, to reduce the transmission latency, it should select the neighboring node that enters listen mode more quickly and satisfies delay constrains. Each entry in the routing table has an additional field to record time of entering listen mode. When a source node wishes to send a data packet to a destination node and discovery that all corresponding entries in routing table or no information is available for destination address, then it performs route discovery process by sending *QUERY* packets. When the node receives a *QUERY* packet, it appends its ID to the *QUERY* packet and forwards it on the basis of the time of entering listen mode and delay constrains. If the node cannot forward the *QUERY* packet, it will just drop it. The low-latency next-hop selection algorithm for table-driven protocols is shown in Algorithm 1. In addition, to prevent the *QUERY* packet from traversing entire network, the packet is dropped if it has traversed more than the maximum hops (*MAXHOPS*).

The low-latency next hop selection mechanism is not directly applicable to on-demand protocols, such as dynamic source routing [23] and prioritized battery-aware routing [29]. On-demand routing protocol discovers for the desired route only when needed. With on-demand protocols, the source node specifies the intermediate nodes along a route that a packet should pass through them to its final destination. The low-latency next hop selection mechanism can be applied when the source node or an intermediate node forwards route request (*RREQ*) during the route discovery process of on-demand protocol. Instead of broadcasting, the *RREQ* packet will be forwarded to the chosen neighbor node that will soon enter the listen mode and satisfies delay constrains until reaching destination node. The low-latency next hop selection algorithm for on-demand protocols is shown in Algorithm 2. Once the destination node receives a *RREQ* packet, a *routereply* (*RREP*) packet is generated and returned to source node. An intermediate node receives a *RREP* packet from its neighbor, which also implies that the intermediate node can reach the destination via that neighbor. As a consequence, the routing path is found. However, the selected routing path might not be the shortest path. This fact is not necessarily an issue, because the shortest path in multi-hop MANETs is not necessarily an optimal path, as has been shown elsewhere [24].

The route discovery process fails if the source does not receive a RREP packet within maximum tolerable round trip time (MTRTT). MTRTT can be estimated on the basis of real-time measurements using exponential weighted moving average method. The source node continues sending

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**Algorithm 1** Low-latency next hop selection for table-driven protocol

```
/* Purpose: To forward a QUERY packet q at an intermediate node m. */
PARAMETERS:
q ← outgoing QUERY packet
PROCEDURE:
Begin
if q.hop_cnt > MAX_HOPS then
    drop q
else
    if q.destination_address ∈ m's routing cache then
        next ← choose a neighbor's address equal to destination_address
        forward q to next
    else
        next ← choose next hop based on time of entering listen mode and delay constrains
        forward q to next
    end if
end if
End
```

**Algorithm 2** Low-latency next hop selection for on-demand protocol

```
/* Purpose: To forward a QUERY packet q at an intermediate node m. */
PARAMETERS:
q ← outgoing QUERY packet
PROCEDURE:
Begin
if q.hop_cnt > MAX_HOPS then
    drop q
else
    next ← choose next hop based on time of entering listen mode and delay constrains
    forward q to next
end if
End
```

RREQ packets until it receives a RREP packet. The packet is forwarded to destination via route path in data routing phase. Although the path to destination is found, nodes forward the data packets on the basis of their routing tables selecting the least power consumption route. The aim of route maintenance process [29] is to ensure the nodes along route path availability any time. As the node is away or power off anytime, route maintenance and dissemination of energy information of the nodes is performed periodically by flooding some number of explore packets. Although the destination node receives the explore packet, it replies with a reply packet to the source by using the reverse path. If the node doses not communicate with the destination for a long time, the node will stop sending explore packet to that destination. The subsequent process is the same as that of the route discovery process.

## 4. THEORETICAL ANALYSIS

In this section, we present the theoretical analysis related to $p$-MANET concerning the average awake time and average delay time. For the theoretical analysis, we assume that there are number of $N$ beacon intervals in one cycle and the upper-layer routing protocol is ideal, which can guarantee delivery.

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### 4.1. Average awake time

We first present results in terms of the amount of awake time, $E(t)$, that a node is busy during a cycle. Note that each node only needs to become active during one beacon interval for one cycle, that is, $\frac{1}{N}$ times. $E(t)$ gives that

$$E(t) = \sum_{i=1}^{N} i \times \frac{1}{N} \tag{2}$$

where $i$ represents the $i$th node in the network. Note that by Equation (2), the total awake time of a node is under different number of beacon intervals. By increasing number of beacon intervals, we are able to reduce the awake time and power consumption of a node. As BW and MTIM are relatively much smaller than DW, the average awake time approximates $\frac{1}{N}$ as $N$ becomes large, as shown in the Figure 3. However, the less frequently awake time increases the transmission delay time. Therefore, the following subsection discusses this trade-off between power consumption and transmission delay.

### 4.2. Average delay time

The average delay time is defined as the average waiting time incurred by a transmitter while trying to indicate to a receiver that it wishes to communicate with it. The expected average amount delay time (hereafter denoted as $E[D]$) is shown in Equation (3). In this equation, the first term, $E[D_\text{p}]$, is the packet delay of the node due to the power saving in the sleep state of $p$-MANET. The next term, $E[D_\text{c}]$, is the packet delay of the node due to the basic access mechanism. Therefore, the average delay time, $E[D]$, is as follows from Equations (4) and (6).

$$E[D] = E[D_\text{p}] + E[D_\text{c}]. \tag{3}$$

For a cycle that contains a number of $N$ beacon intervals, a node may wait a number of $i$ beacon interval to transmit packets to the destination node. When packets try to transmit to the receiver, both of transmitter and receiver are just at the same wake up time, they do not have to wait. On the contrary, a receiver works in the sleep time when transmitter arrives, and they have to wait $i$ beacon intervals. In this case, $E[D_\text{p}]$ is given by Equation (4).

$$E[D_\text{p}] = \frac{1}{N}\sum_{i=0}^{N-1} \times 1 = \frac{1}{N} \times 0 + \frac{1}{N} \times 1 + \frac{1}{N} \times 2 \ldots + \frac{1}{N} \times (N-1) = \frac{N-1}{2}. \tag{4}$$

Now the $E[D_\text{c}]$ due to the basic access mechanism, called distributed coordination function, is basically a CSMA/CA MAC protocol [18], which can be computed by Equation (5). When a node with a new packet transmits, the channel activity is monitored. If the channel is idle for a period equal to distributed interframe space (DIFS), then the node transmits the packet with probability $p$, whereas with probability $(1-p)$, it delays the packet transmission to the next time cycle. Otherwise, if the node is sensed as channel busy, the node persists to monitor the channel at next cycle until it is measured idle for a period of DIFS. At this time, the node generates a random backoff interval before retransmission. Moreover, the binary slotted exponential backoff is used with CSMA/CA. Whenever a backoff occurs, the backoff time is set from a uniform distribution over the interval $[0, CW]$, whereas the contention window (CW) will be doubled for a retry and reset a new packet.

Therefore, the derivation of $E[D_\text{c}]$ follows from Equations (5) and (6). The first term in Equation (5) is the successful transmission at the first cycle with probability $p$. Otherwise, a transmitter needs to wait for the next cycle, that is, number of $N$ beacon intervals, to retransmit with contention until transmission succeeds. For example, the second term is the successful transmission at the second cycle whereas a transmitter has failure transmission at the first cycle.

$$
\begin{aligned}
E[D_{\mathrm{c}}] &= p\times 1+(1-p)\times p\times(N+1) + (1-p)^2 \times p \times (2N+1) + (1-p)^3 \times p \times (3N+1) + \dots \\
&= p + (1-p)\times p + (1-p)\times p \times N + (1-p)^2 \times p + (1-p)^2 \times p \times 2N + \dots \\
&= p \times \frac{1}{1-(1-p)} + \sum_{i=1}^{\infty}(1-p)^i \times p \times i \times N \\
&= 1 + i \times \sum_{i=1}^{\infty}(1-p)^i \times p \times N \\
&= 1 + \left(\frac{1-p}{p^2}+1\right) \times p \times N.
\end{aligned}
\tag{5}
$$

Equation (5) implies that

$$E[D_{\mathrm{c}}] = 1 + \left(\frac{1-p}{p} + p\right) \times N \tag{6}$$

where $p$ is the probability that a transmission attempt is successful, $i$ is the number of transmission delay, and $N$ is the total number of beacon interval.

### 4.3. *Probability of successful transmission*

The probability that a transmission attempt successfully occurs in a slot time denoted as $\mathbb{P}$ is analyzed. To compute $\mathbb{P}$, we analyze what can happen in a random chosen slot time of MTIM window. In Equation (7), $p_{\mathrm{m}}$ means that a transmission occurring on the channel is successful and is given by the probability that exactly one node transmits on a channel during a CW. The term $T_{\mathrm{c}}$ is the average number of contention exists, that is, there are $T_{\mathrm{c}}$ nodes that receive ACK from the intended node during $T_{\mathrm{c}}$ times contention.

$$\mathbb{P} = p_{\mathrm{m}}^{T_{\mathrm{c}}}. \tag{7}$$

To compute the probability that there is at least one transmission in the considered slot time and exactly one node successfully transmit, we use the same assumption and analysis results as those papers in [31–33]. Suppose there are number of $m$ contention nodes in the MTIM window and each transmits with probability $\tau$ to random choice slot. In Equation (8), let $P_{\mathrm{tr}}(m)$ be the probability that there is at least one transmission in the considered slot time. In Equation (9), the probability $P_{\mathrm{m}}$ means that a transmission occurring on the channel is successful and is given by the probability that exactly one node transmits on a channel, conditioned on the fact that at least one node transmits.

$$P_{\mathrm{tr}}(m) = 1-(1-\tau)^m. \tag{8}$$

$$P_{\mathrm{m}} = \frac{m\tau \times (1-\tau)^{m-1}}{P_{\mathrm{tr}}(m)}. \tag{9}$$

In MTIM windows, if node $A$ has buffered packet destined for node $B$, node $A$ may send MTIM frame to intended node during this interval. Upon node $A$ receiving ACK from node $B$, both $A$ and $B$ will be awake for transmitting packet in DW. However, the collision problem is possible. If the node senses the channel busy, the backoff time is uniformly chosen within the range $(0, w-1)$ defined as the CW. Note that MTIM window is divided in slot $[0, w-1]$, which consists of $w$ slots numbered 0 through $w-1$. At the first transmission attempt, $CW = CW_{\min}$, and it is doubled at each retransmission up to $CW_{\max}$. The values suggested in draft standard [4] are $CW_{\min} = 32$ and $CW_{\max} = 256$. At each CW, that is, each contention, there is exactly one node receiving ACK from intended node during $\mathrm{avg}[C_{\min}, C_{\max}]$. Consequently, the average number of contention exists in MTIM window as shown in Equation (10). After MTIM window, there are $T_{\mathrm{c}}$ nodes that successfully notice intended nodes that wake up in order to transmit packet in DW. For example, in Figure 4, nodes $A$ and $C$ receive ACK form node $B$ at different CW, respectively.

$$T_{\mathrm{c}} = \frac{w}{\mathrm{avg}[C_{\min}, C_{\max}]}. \tag{10}$$

## 5. PERFORMANCE EVALUATION

This section evaluates the performance of a $p$-MANET by simulation. The simulation models a network of 50∼200 mobile nodes placed randomly within a $1000 \times 1000$ m area. The *ad hoc* on-demand distance vector routing protocol is used as the underlying routing protocol for MANET. The traffic load of each route follows a Poisson process with mean of 1 connection per second. The power capacity, radio propagation range, and channel capacity of each node are 100 J, 250 m, and 2 Mbits/s, respectively. The power model that is shown in Table II is used in the simulation, where $L$, the packet length, is set to 1024 bytes. The random waypoint model [25] is applied as the mobility model, in which the pause time is set to 20 s. The mobility speed varies from 0 to 40 m/s, and, unless otherwise specified, the default mobility speed is set to 5 m/s. Each mobile node utilizes the SHA-1 hash function and a unique node ID (MAC address) to determine the beacon interval in which to enter the listen mode. Multiple runs, each of 600 simulations, are conducted for each scenario.

The performance of the $p$-MANET (P) is compared with that of the quorum-based protocol (Q) with $5 \times 5$ matrices [11] in terms of three metrics—fraction of nodes that survive, neighbor discovery time, and transmission latency. Firstly, the fraction of surviving nodes is defined as the number of surviving nodes over the total number of nodes. This commonly applied performance metric is very important for evaluating power-saving protocols [11, 26, 27]. It is evaluating by running each simulation until all nodes have exhausted their power capacity. Secondly, the neighbor discovery time is defined as the average time required to discover a newly joined node. In MANETs, a mobile node can be aware of its neighboring nodes by listening to the signals that they transmit. However, if a mobile node enters the PSM, then it will not be able to notice a newly joined node. But, numerous protocols, including routing protocols, require detailed information about neighboring nodes. Therefore, the time taken to discover a newly joined neighbor is an important index for power-saving protocols. Finally, the transmission delay is defined as the waiting time incurred by a transmitter while trying to indicate to a receiver that it wishes to communicate with it. Table III summarizes notation used in the simulation.

### 5.1. *Fraction of surviving node*

This section evaluates the fraction of surviving nodes under several scenarios of (i) beacon interval length, (ii) various node density, and (iii) mobility speeds of nodes. In the following simulations, the BW and the MTIM window are set to 4 and 16 ms, respectively.

*5.1.1. Impact of beacon interval length and node density.* Figure 7(a)–(c) plots the impact of the beacon interval on the survival ratio when the number of nodes is set to 100, 150, and 200. The beacon interval varies from 100 to 400 ms. Obviously, the lifetime of the $p$-MANET increases with

Table II. Power consumption parameters used in simulations.

| Status | Transmit | Receive | Idle | Sleep |
|---|---|---|---|---|
| Power consumption | $454 + 1.9 \times L$ μJ/packet | $356 + 0.5 \times L$ μJ/packet | 843 μJ/ms | 27 μJ/ms |

Table III. Power consumption parameters used in simulations.

| Notation | Meaning |
|---|---|
| P | $p$-MANET |
| Q | Quorum-based protocol [11] |
| Q(5) | The awaking ratio of quorum-based protocol is 0.36 (9/25) |
| P(3) | The awaking ratio of $p$-MANET is 0.33 (1/3) |
| P(5) | The awaking ratio of $p$-MANET is 0.2 (1/5) |
| P(7) | The awaking ratio of $p$-MANET is 0.14 (1/7) |
| P(9) | The awaking ratio of $p$-MANET is 0.11 (1/9) |

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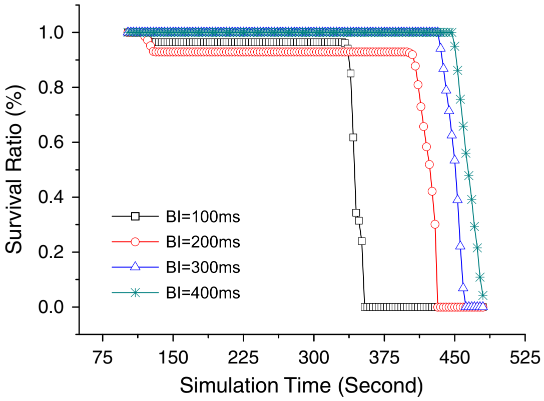
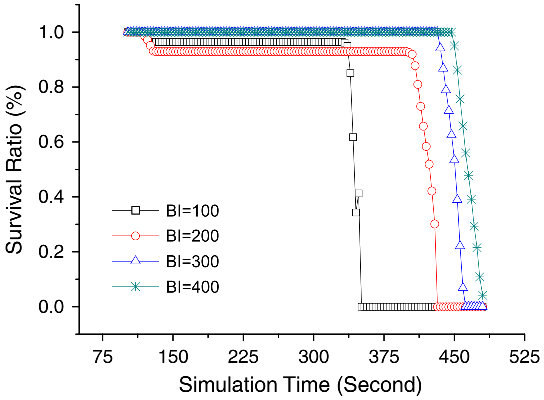
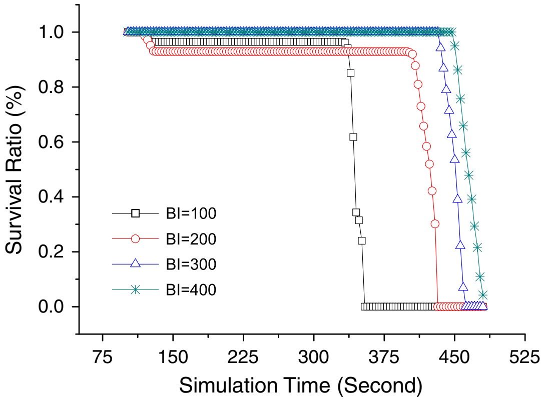


(a) 100 nodes



(b) 150 nodes

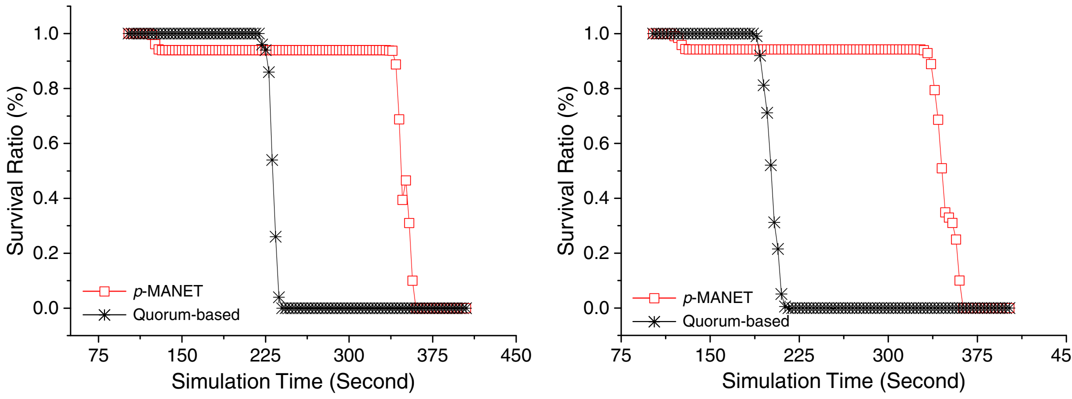


(c) 200 nodes

Figure 7. Impact of beacon interval length on fraction of surviving nodes.

the beacon interval, regardless of whether the network is a sparse or dense. As the beacon interval increases, the number of beacons to be sent declines. However, increasing the interval also increases the neighbor discovery delay, as will be discussed later.

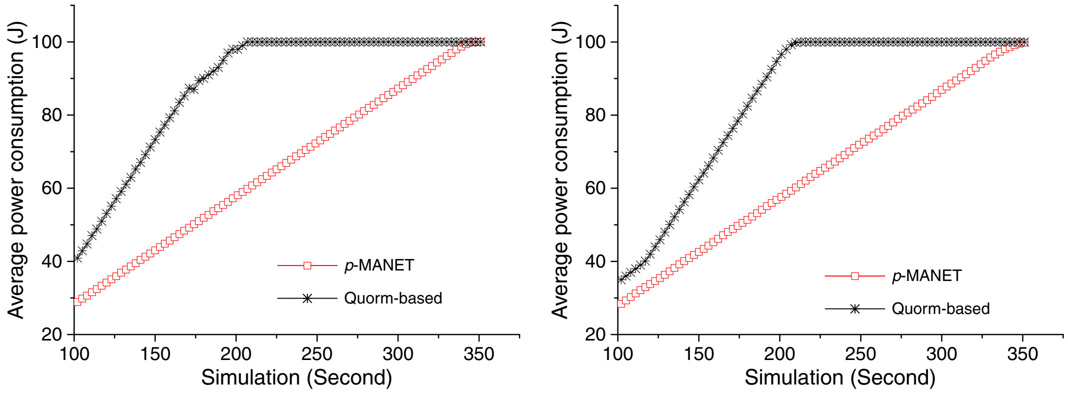
Figures 8 and 9 present the impact of the number of nodes on the survival ratio and on the average power consumption with a beacon interval of 100 ms, respectively. The *p*-MANET and quorum-based protocol are compared, where number of node is set to 50 and 200. Figure 8 indicates that the *p*-MANET yields a significantly higher fraction of surviving nodes than does the quorum-based protocol. Meanwhile, Figure 9 shows that *p*-MANET is clearly energy saving than the quorum-based protocol.



(a) 50 nodes

(b) 200 nodes

Figure 8. Impact of various node densities on fraction of surviving nodes with $BI = 100$ ms.



(a) 50 nodes

(b) 200 nodes

Figure 9. Impact of various node densities on fraction of average power consumption with $BI = 100$ ms.

The lifetime of the $p$-MANET is almost independent of the number of nodes, because the sleep time of each node in $p$-MANET is also almost independent of the number of nodes. According to Figures 8 and 10, node density influences the performance of the quorum-based protocol more strongly than that of $p$-MANET. For example, for $p$-MANET, as the various number of nodes varies, the fraction of surviving node remains almost constant; for the quorum-based protocol, the fraction of surviving nodes varies. Moreover, the network lifetime and the average power consumption of the quorum-based protocol decreases markedly and more rapidly than that of $p$-MANET. The simulation results demonstrate that the scalability and energy conservation of $p$-MANET are better than those of the quorum-based protocol for various node densities.

*5.1.2. Impact of number of beacon intervals.* Figures 10 and 11 compare the survival ratio and the average power consumption of a mobile host in $p$-MANET with that of the quorum-based protocol, respectively. The waking ratio of the quorum-based protocol with a 5×5 matrix, Q(5), is 0.36 (9/25). Recall that for $p$-MANET, the waking ratio is approximately the inverse of the number of beacon intervals. Hence, the waking ratios of $p$-MANET are 0.33 P(3) and 0.11 (P(9)) when the numbers of beacon intervals are 3 and 9, respectively. In Figure 10, the improvement of the survival ratio of $p$-MANET over that of quorum-based protocol thus ranges from 8.3% to 71%. Meanwhile, the average power consumption of $p$-MANET is lower than of quorum-based protocol.

*5.1.3. Impact of mobility.* Figure 12 evaluates the effect of the mobility speed of nodes on the fraction of surviving nodes. Mobility speed of mobile nodes will incur higher energy consumption

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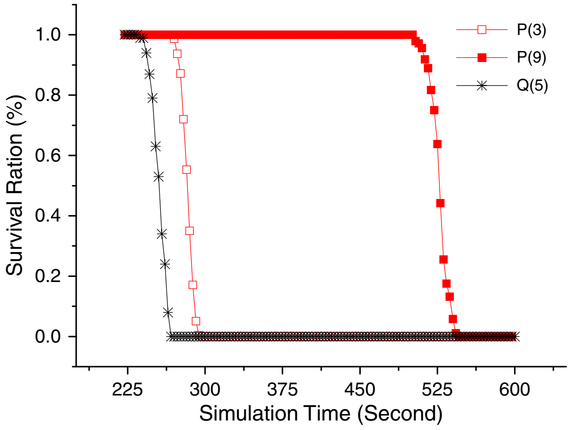

Figure 10. Impact of number of beacon intervals.

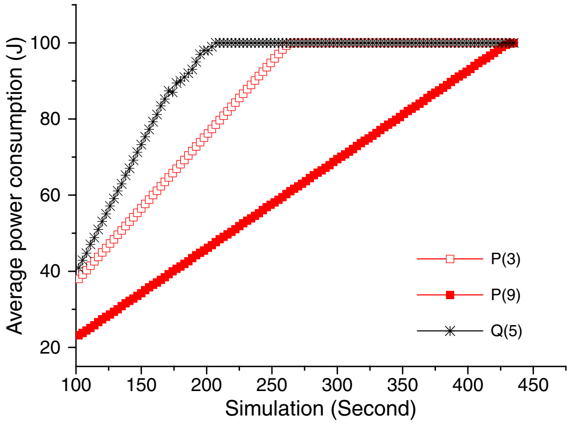

Figure 11. Impact of power consumption with 50 nodes.

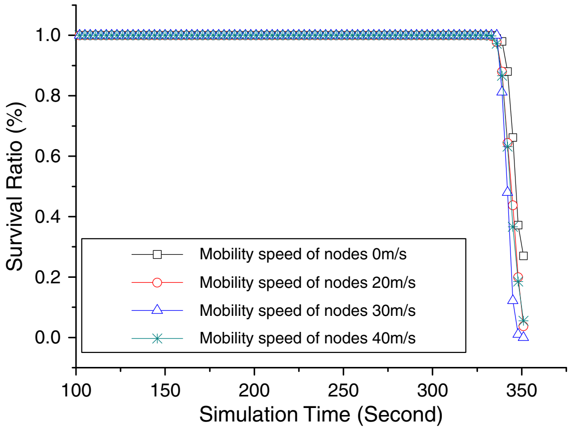

Figure 12. Effect of mobility speed of nodes.

because mobile nodes may spend more energy in retransmitting packets. However, mobility has very little impact on the surviving ratio of nodes in our experiments. Figure 12 shows that mobility speed of nodes has little impact on the performance of *p*-MANET, because the energy consumption of *p*-MANET is mainly controlled by the number of beacon intervals.

### 5.2. *Neighbor discovery time*

In this section, the neighbor discovery time is evaluated for various beacon intervals and super frame sizes. Figure 13 demonstrates that the neighbor discovery time increases almost linearly with the beacon interval. The notations in Figures 13 and 14 are indicated in Table III. The neighbor discovery time of $p$-MANET is no more than 500 ms, whereas that of the quorum-based protocol is approximately 800∼3000 ms. Obviously, $p$-MANET substantially outperforms the quorum-based protocol. A trade-off between the neighbor discovery time and the network lifetime of the MANETs is observed. For high dynamic MANETs with a heavy traffic load, the beacon interval should be set shorter to increase the accuracy of the neighbor information and thereby the routing performance. A long beacon interval is preferred for stable MANETs. Figure 14 plots the impact of the number of beacon intervals on the neighbor discovery time. Again, as the number of beacon intervals increases, the node is less able to enter the listen mode, and so the neighbor discovery time increases. However, the increase is not as significant as that in Figure 13. These results also demonstrate that the mean neighbor discovery time increases by approximately one half of the beacon interval as the number of beacon intervals increases by one cycle. Notably, the neighbor discovery time of $p$-MANET still outperforms that of the quorum-based protocol. In summary, the proposed $p$-MANET does not suffer from the long neighbor discovery time problem.

### 5.3. *Transmission latency*

Figure 15 plots the transmission latency for the $p$-MANET and quorum-based protocols under various beacon interval lengths. Figure 15 demonstrates that for the quorum-based protocol, the transmission latency grows significantly with the beacon interval length. The notations in Figures 15 and 16 are indicated in Table III. However, for $p$-MANET, it increases less rapidly, because the low-latency next hop selection mechanism of $p$-MANET adopts heuristic strategies, which effectively reduce the transmission latency. Figure 16 plots the transmission latency for the $p$-MANET and

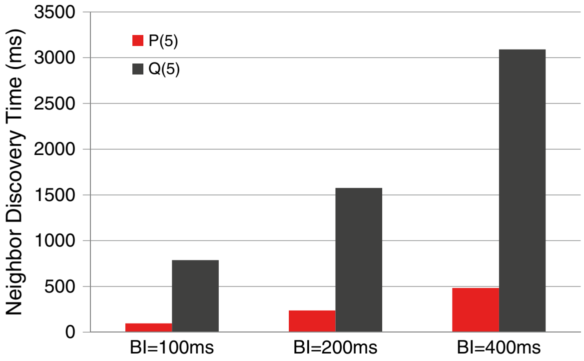

Figure 13. Impact of beacon interval length on neighbor discovery time.

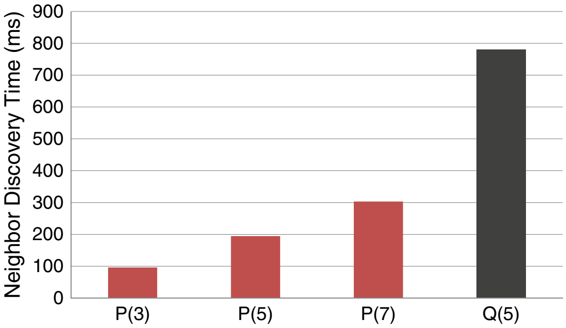

Figure 14. Impact of number of beacon intervals on neighbor discovery time.

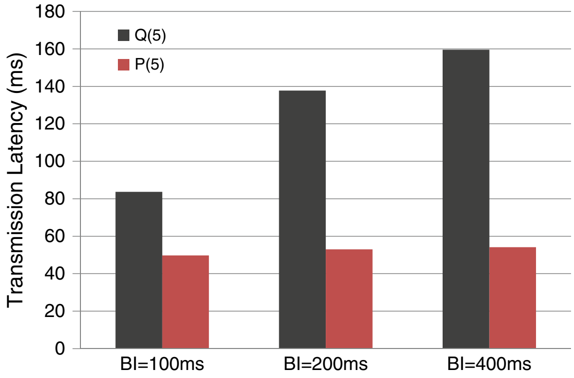

Figure 15. Impact of beacon interval length on transmission latency.

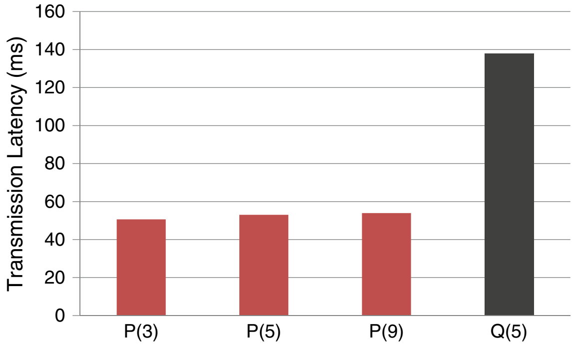

Figure 16. Impact of number of beacon intervals on transmission latency.

quorum-based protocols under various number of beacon intervals. The beacon interval length is fixed to 200 ms. $p$-MANET still outperforms the quorum-based protocol. From Figure 16, the proposed $p$-MANET does not suffer from the long neighbor discovery time problem. Consequently, the number of beacon intervals does not affect the transmission latency very much.

### 5.4. *Out of synchronization percentage and synchronization accuracy*

Table IV presents the performance of MTSP. When the maximum clock skew exceeds 224 µs, the network is considered to be unsynchronized in that beacon interval. Table IV also indicates that the out of synchronization percentage of MTSP remains less than 0.1% in all simulated cases. The average maximum clock skew of MTSP is less than 50 µs in all cases, which is far less than the out of synchronization threshold of TSF, 224 $\mu$s.

Intuitively, the synchronization-based power-saving protocol is affected by clock skew. Hence, the effect of clock skew on the performance of $p$-MANET is evaluated. In this simulation, the number of nodes is set to 100 and the beacon interval is set to 100 ms. The maximum clock skew is set to 50 $\mu$s, as shown in Table IV. Figure 17 shows that the network lifetime is 351 s without clock skew and 340 s with clock skew in the simulation, respectively. Furthermore, the clock skew dramatically reduces the node survival ratio after 250 s in the simulation, revealing that clock skew causes a node

Table IV. Out of synchronization percentage and synchronization accuracy of MTSP.

| Number of node | $BI = 50$ ms | $BI = 100$ ms | $BI = 200$ ms |
|---|---|---|---|
| Out of synchronization percentage | 0.07 | 0.1 | 0.1 |
| Average maximum clock skew (µs) | 31.1 | 39.1 | 47.3 |

MTSP, Multi-hop Time Synchronization Protocol.

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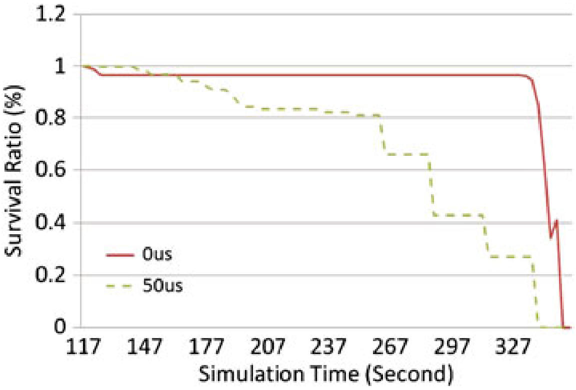

Figure 17. Impact of simulation time on survival ratio.

to have to consume additional power to communicate with other nodes. From Figure 17, the performance of $p$-MANET is slightly affected by clock skew. Thus, the synchronization protocol remains important to synchronization approaches.

## 6. CONCLUSIONS AND FUTURE WORK

Power conservation is very important to prolong the battery life of important devices. This work proposed a novel efficient power-saving MAC protocol for multi-hop MANETs, called $p$-MANET. $p$-MANET consists of three mechanisms—the hibernation mechanism to prevent the consumption of power for unnecessary tasks, the beacon inhibition mechanism solves beacon storm problem, and the low-latency next hop selection mechanism offers heuristic strategies to select efficiently the next-hop node for packet forwarding. To confirm the effectiveness of $p$-MANET, we present the theoretical analysis related to $p$-MANET concerning the average awake time and average delay time. And extensive simulations were performed, and the results revealed a power saving of over 70%, a low neighbor discovery time, and a low transmission latency with $p$-MANET. Several issues related to $p$-MANET require further investigation. The authors are developing upper-layer protocols, such as a power-aware routing protocol and power-aware application protocols on the basis of the cross layer design. Therefore, the overall routing performance requires further evaluation. Power consumption and message overhead will be taken into account, with the expectation of obtaining a more scalable solution.

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