A Passive Self-Configuration MAC Protocol for IEEE 802.11-Based Multi-Hop MANETs

Kuei-Ping Shih, Sheng-Shih Wang, and Hsieh-Wei Lin
Department of Computer Science and Information Engineering
Tamkang University
Tamshui 251, Taipei, Taiwan
kpshih@mail.tku.edu.tw

Abstract
The paper proposes a passive self-configuration MAC protocol (PSC-MAC) for IEEE 802.11-based multi-hop MANETs (MH-MANETs). PSC-MAC focuses on passively determining multiple supervising sets, each of which consists of some power-rich stations, supervisors, to be in charge of the network management. The main idea of PSC-MAC is beacon interleaving, which guarantees supervisors in different supervising sets are able to transmit their beacons in the different beacon intervals. Each station in PSC-MAC enables to dynamically and passively transit its role to either supervisor or member by means of the proposed four rules. Simulation results show that PSC-MAC outperforms IEEE 802.11 and some existing approaches in network merging, network synchronization, and power saving.

1 Introduction
In an infrastructure network of IEEE 802.11, network management is effortless due to the existence of access points (APs). For lack of APs, network management, such as self-configuration in multi-hop mobile ad-hoc networks (MH-MANETs) is obviously complicated [1]. Much research has proposed numerous efficient solutions to the issue [2, 3].

Generally, a MH-MANET consists of multiple IBSSs (Independent Basic Service Sets) self-controlled by all STAs. The challenges, including network synchronization, network partitioning, and power saving should be tackled in the development of the management mechanism in such networks [2]. Since there is no APs and inconsistent packet delay, incurred by unpredictable mobility and radio interference, time synchronization in MH-MANETs may not be achieved. The problem is especially obvious in the dense network [4]. If having the imprecise clocks, the STAs in a MH-MANET are probably unaware of their immediate neighboring STAs because of inconsistent awake/asleep schedules. Thus, the STAs, actually belonging to one IBSS, may form multiple IBSSs.

Obviously, the problems above are resulted from the lack of APs in the network. Although all STAs are equivalent and there exists no APs in a MH-MANET, we intend to select some suitable STAs, which play the AP-like roles in the network, to cope the problems, including network synchronization, network partition, and power saving. The paper proposes an efficient MAC protocol, passive self-configuration protocol (PSC-MAC), for IEEE 802.11-based multi-hop MANETs. PSC-MAC is mainly to dynamically determine the STAs, called supervisors, with much energy to be in charge of network management in a decentralized and passive fashion. All supervisors are divided into multiple sets, supervising sets. The STAs in the individual set only need to transmit their beacons in one beacon interval in a Beacon Interleaving Cycle (BIC), which is a repeated period for the supervisor to transmit the beacon.

PSC-MAC exploits the beacon interleaving scheme to inhibit two neighboring supervisors from beacon transmission in the same beacon interval. Additionally, numerous elegant rules are taken into account for a STA to invoke role determination when the network is partitioned, the network has an isolated STA, or a STA has insufficient energy. Overall, PSC-MAC has significant advantages: (1) PSC-MAC incurs less communication overheads because supervisor determination is achieved in the passive manner. (2) PSC-MAC is suitable for the variation in MH-MANETs with the characteristic
of the self-configuration. (3) PSC-MAC achieves network synchronization via beacons issued from supervisors. (4) PSC-MAC increases the longevity of the network due to power-rich supervisors.

The remainder of this paper is organized as follows. Section 2 formulates the network management problem, and mentions the basic concept of the proposed protocol. Then, a novel MAC protocol, PSC-MAC, is proposed in Section 3. Meanwhile, the simulation results are shown in Section 4. Finally, Section 5 presents conclusions and future research directions.

2 Preliminaries

This section first mentions the issues of network management in MH-MANETs, and then gives the basic concept of PSC-MAC.

2.1 Problem Statement

Generally, network synchronization, power saving, and network partitioning should be mainly considered in designing a mechanism for network management.

- Network Synchronization

IEEE 802.11 provides the CSMA/CA mechanism for each STA to contend to send a beacon for network synchronization in a single-hop MANET [1]. However, network synchronization is unreachable if a STA with faster clock unsuccessfully contends to send a beacon. Consider a MH-MANET, if there exists a supervisor responsible for synchronization within each IBSS, all STAs are able to be synchronized to such supervisor via beacon transmission.

- Power Saving

Numerous approaches to power saving and power management are developed for MANETs [5, 6]. The main idea of the protocols is to turn the radio off if a STA has no packet to transmit or receive. A CDS-based protocol is proposed in [7], in which some STAs are selected as the coordinators, which should keep awake for the whole beacon interval. Such coordinator obviously consumes the battery power quickly, and consequently fails to work due to energy exhaustion.

- Network Partitioning

The power saving mechanism (PSM) in IEEE 802.11 is designed for a single-hop network, in which all STAs are assumed to be time-synchronized [1]. In a MH-MANET, two STAs within the transmission ranges of each other may follow the inconsistent awake/asleep schedules. Thus, these two STAs are unable to directly communicate with each other. Such problem is likely to cause long packet delay, especially for data transmissions between different IBSSs.

In a MH-MANET, the network probably comprises several IBSSs. Since all supervisors in a MH-MANET independently work in their own IBSSs, the actually connected IBSSs may be consequently partitioned. The scenario probably makes many existing routing protocols failed in route discovery [6].

To effectively determine the supervisor, we summarize the following properties that supervisors have to satisfy.

- Each supervisor should have at least one neighboring supervisor.
- Two neighboring supervisors should transmit the beacons in the different beacon intervals.
- Each STA in the network should be served by at least one supervisor.
- The supervisor should be a power-rich STA in the network.

2.2 Basic Concepts

Figure 1 shows the main idea, beacon interleaving, of PSC-MAC. The main goal of beacon interleaving is to enable the supervisors in different supervising sets in turn to wake up to transmit their beacons in different beacon intervals. The supervising sets really achieve network management in each BIC, defined as below.

**Definition 1** Beacon Interleaving Cycle (BIC) is composed by two or more beacon intervals, which is a repeated period for beacon interleaving. BIC is a system parameter, which is predetermined and is well-known by all STAs.

In the paper, we use $BI$ and $N_{BI}$ to represent beacon interval and the number of BIs in a BIC, respectively.

As Figure 1 illustrates, all STAs with the same transmission range initially keep on listening for a
Suppose STAs $A$, $C$, $E$, and $G$ successfully transmit the beacons in the second BI. These STAs finally form the second supervising set. Obviously, STAs $B$, $D$, and $F$ with the supervisors roles in the first BI will respectively hear the beacons from STAs $A$ and $C$, $C$ and $E$, as well as $E$ and $G$. STAs $B$, $D$, and $F$ require revoking their supervisor roles and becoming the members in the second BI. Additionally, STA $H$ also needs to cancel the beacon transmission owing to the receipt of the beacon from STA $G$.

3 PSC-MAC Protocol

Beacon interleaving is the important concept of the PSC-MAC protocol, so the section will describe such concept in detail. Then, four rules will be introduced to assist in supervisor determination and role transition in a passive manner. Meanwhile, the residual battery power of the STA is also considered in PSC-MAC.

3.1 Beacon Interleaving

Recall that all supervisors in PSC-MAC are connected. There exists a connection between two neighboring supervisors. These supervisors are likely to transmit beacons in the same beacon interval for lack of any coordination scheme. To avoid a scenario, where the STAs within the ranges of multiple supervisors will not receive any beacon in case of collisions. Each STA needs to listen for a random period of time before issuing its beacon, and requires cancelling its beacon once hearing the beacon from the other STAs. This paper proposes the Last Declaration Wins rule to relieve the problem. The Last Declaration Wins rule enables the supervisor, which last transmits the beacon remains the role of the supervisor, while other supervisors require becoming the members in this BI. Obviously, such rule not only effectively brings the advantage of the passive manner in supervisor determination, but also really generates only one supervisor in a BI.

Imagine that two supervisors are able to transmit their beacons in the different BIs for each BIC. Network management will be well achieved. Inspired by the concept, the beacon interleaving scheme, whose main goal is the suppression of beacon transmissions from two neighboring supervisors in the same BI, is proposed in the paper. The scheme is able to efficiently reduce the overlap between the regions served by two supervisors in the same BI.

In Figure 2, a BIC is assumed to consist of two BIs (i.e., $N_{BI} = 2$). Two neighboring supervisors (e.g., $A$ and $B$, $B$ and $C$, as well as $C$ and $D$) obviously transmit the beacon in the distinct BIs. The supervisors are responsible for network management only in the individual BIs, in which these supervisors transmit the beacons. Significantly, the network is well controlled by two supervising sets, each of which includes the STAs transmitting the beacons in the same BI. Namely, STAs $A$ and $C$, playing the supervisor roles, form a supervising set in the first BI, and STAs $B$ and $D$ plays the roles of

![Figure 1: Key idea of PSC-MAC. The gray and white circles are respectively the supervisor and member. The dark circle in the different beacon interval means the supervisor, requiring transmitting the beacon.](image-url)
members in the BI. Another supervising set comprises STAs B and D, whose roles are the supervisors in the second BI. In the meanwhile, STAs A and C are the members, accordingly. The supervisors in such two sets require transmitting the beacons interleaved in the first and the second BIs in a BIC, respectively.

3.2 Supervisor Determination

To guarantee a STA to be able to dynamically become the supervisor or member in the passive manner, the paper exploits numerous rules, including deficiency, isolation, partition, and border rules.

- **Deficiency Rule:** If a STA hears no beacon in a BI, then the STA requires becoming the supervisor in the BI.

  For lack of supervisors, network management is probably not achieved. In Figure 3, assume that STAs A and C are STA B’s neighboring STAs, and all STAs have the same transmission range. Suppose STAs B and C are supervisors, and transmit their beacons in the first and second BIs, respectively. Thus, STA A is able to hear the beacon from supervisor B in the first BI, while hears no beacon in the second BI. Obviously, the number of supervisors in the network is insufficient. Therefore, STA A should become the supervisor in the second BI.

- **Isolation Rule:** If a STA only hears the beacon from the same supervisor in each BI, then the STA requires becoming the supervisor in any one of BIs.

  Consider a network shown in Figure 4, where supervisor A is assumed to transmit the beacon in each BI. Because always hearing the beacon from STA A in each BI, STA B realizes that STA A is an isolated STA. Motivated by beacon interleaving, STA B should become the supervisor in any one of BIs (e.g., the 2nd BI in Figure 4) in a BIC to assist STA A in network management.

- **Partition Rule:** If a supervisor has heard one beacon in a BI, and hears at least one beacon in any other BI, the supervisor requires transmitting the beacon in the BI, in which less than two beacons are heard.

- **Border Rule:** If a supervisor has heard one beacon in a BI, and never heard more than one beacon in any other BI, the supervisor requires cancelling the beacon transmission in any one of BIs.

  As Figure 5 shows, STA B hears the beacons from STAs A and C in the first BI, and three STAs all hear no beacon in the second BI. Because the supervisors should be connected, supervisors A and C are obviously disconnected currently. STA B requires becoming the supervisor in the BI rather than the first one for beacon transmission. Additionally, STAs A and C also require becoming the supervisors in accordance with the deficiency rule.

  If STAs A and C both successfully contend for beacon
beacon transmission prior to STA B, these two STAs should be regarded as the supervisors in both BIs in a BIC. Such scenario really make the beacon interleaving scheme invalid. Therefore, STA B requires becoming the supervisor for beacon transmission in the second BI. In addition, STAs A and C need to cancel their beacon transmissions in the second BI for the avoidance of the circumstance, in which STAs A and C always successfully contend for beacon transmission.

3.3 Operation

The operation of PSC-MAC is similar to that in IEEE 802.11. A STA requires awakening at the TBTT and keeps on listening during the whole ATIM window. Unlike IEEE 802.11, in which all STAs contend for beacon transmission, PSC-MAC guarantees that beacons are actually transmitted only by supervisors. The supervisors in PSC-MAC are determined in the passive manner according to the residual battery power of the STA and status of the network.

Based on various power cost functions, PSC-MAC enables the user to preset the power threshold, \( \eta \), by which the STA is capable of adjusting its operation mode. Let \( E_r \) be the residual energy of a STA. A STA enters the active mode if \( E_r \geq \eta \), whereas the STA enters the PS mode in case \( E_r < \eta \). PSC-MAC employs the Power Management field, one of the IEEE 802.11 frame control field, to indicate the operation mode of a STA. The field is denoted as PS\_flag. The values of 0 and 1 indicate that the STA is in the active and power-saving modes, respectively.

In PSC-MAC, a STA has five states: Initial state, Active\_Supervisor state, Active\_Member state, PS\_Supervisor state, and PS\_Member state.

- **Initial state**

A STA is set to be in the Initial state when it turns the radio on.

- **Active\_Supervisor state**

The state of a supervisor in the active mode. A STA in the state periodically transmits beacon, whose PS flag is 0, to its neighboring STAs. Meanwhile, the STA keeps on listening for beacon(s) for role transition in the passive manner.

- **Active\_Member state**

The state of a member in the active mode. Similar to the STA in the Active\_Supervisor state, the STA in the Active\_Member state also passively hears the beacon(s) and invokes role transition according to the proposed rules.

- **PS\_Supervisor state**

The state of a supervisor, whose \( E_r < \eta \). A STA requires transiting to a PS\_Supervisor if there exists no Active\_Supervisor STAs in the vicinity of the STA, the STA receives no any beacon.

- **PS\_Member state**

The state of a member, whose \( E_r < \eta \). The STA in the PS\_Member state requires keeping on listening for the receipt of beacons, and changes to the PS\_Supervisor state in case of no beacon received.

Figure 6 illustrates the transitions among the states. In principle, when a STA turns its radio on, it stays in the initial state. The STA keeps on listening for \( N_{BI}+1 \) BIs to observe the status of beacon interleaving for role transition. During the period of listening, the STA becomes either the supervisor or member, depending on the proposed rules. In a BIC, the supervisor requires transmitting the beacon in accordance with the beacon interleaving approach, but the member synchronized with the neighboring supervisors should keep on listening. Once any one of the rules is fired, role transition will be invoked. If there exists no STAs within the transmission range of a STA, such STA alone will form a network. Otherwise, it will join the existing network.

Once joining another IBSS, the STA is able to realize whether BSSIDs of itself and its neighboring nodes are identical or not. To efficiently merge the different networks, the paper requires a STA with the smaller BSSID joining the IBSS, having the larger BSSID. The strategy is called the **Large**
**BSSID Wins** (LBW) rule. Once successfully joining an existing network, a STA can dynamically determine its role by means of the proposed rules.

When a supervisor turns off or leaves its original IBSS, the BI, in which such supervisor is responsible for transmitting the beacon, is automatically released. All neighboring STAs of the power-off supervisor then contend for the new supervisor in such BI. In case a member turns it radio off, the network remains unchanged because the beacon transmission also works well.

### 4 Performance Evaluations

In this paper, we conduct numerous simulations to evaluate the performance of PSC-MAC. The main concerns in our simulations involve network mergence time, power consumption, and network synchronization. Additionally, we also validate the performance of PSC-MAC in comparison with the IEEE 802.11 mechanism and the protocol addressed in [6].

#### 4.1 Simulation Environment

The network designed in our simulation is a grid topology, within which 100 STAs are uniformly deployed. The grid size, $r$, (namely, the distance between two neighboring STAs) ranges from 0m to 250m with a step of 50m. Table 1 shows the network parameters used in the simulation. The power consumption parameters, such as the transmitting, receiving, idle, and sleeping power are 1327.20mW, 966.96mW, 843.72mW, and 66.36mW, respectively [8].

#### 4.2 Simulation Results

The network density and mobility significantly lead to different results in multi-hop MANETs. We, thus, perform excessive simulations to evaluate the influences of these factors on PSC-MAC in reliability, power consumption, and network synchronization. The variation of network density is achieved by changing the value of the grid size, and the mobility is implemented by turning the supervisors off with an interval of 500µs.

##### 4.2.1 Network Mergence

Figure 7 shows the simulation result about network mergence. The approach, termed IEEE 802.11+LBW, is based on the operation of IEEE 802.11, and exploits the LBW rule to deal with the network mergence. We devise another scheme, Large Node Number Wins (LNNM) rule, by which the network with less STAs is merged into another one with more STAs. Obviously, IEEE 802.11+LBW incurs difficulty in network mergence in case of large grid size owing to packet collisions. However, the times for network mergence in LBW and LNNW both slightly and steadily increase with the increase of grid size. We reason that beacon transmission is always controlled by the supervisors, and then collisions are markedly diminished.

##### 4.2.2 Power Consumption

We compare PSC-MAC with the IEEE 802.11 active mode, PS mode, and Dominating-Awake-Interval (DAI) protocol [6]. The scenario considered in the simulation is that each STA has the same initial energy, 100 joules. In Figure 8,
the times, at which STAs exhaust their energies, in PSC-MAC, DAI protocol, IEEE 802.11 active mode, and IEEE 802.11 PS mode are approximately 80 min, 40 min, 60 min, and 20 min, respectively. With the support of the proposed power-saving mechanism, PSC-MAC enables the active supervisor to dynamically become an active member or PS supervisor. Thus, PSC-MAC significantly outperforms other approaches in power consumption.

Note that DAI protocol requires a PS STA staying awake for at least about half of beacon interval in each beacon interval. Such method wastes much power compared to the IEEE 802.11 PS mode. In addition, the STA using the IEEE 802.11 active mode obviously exhausts its energy quickly due to no sleeping.

We further simulate the network lifetime for various approaches in terms of the different grid sizes. The network lifetime means the time, at which the first STA exhausts it energy. In Figure 9, the network lifetime of PSC-MAC is significantly later than those in other protocols. In principle, the number of STAs responsible for beacon transmission is invariant due to the constant $N_{BI}$, especially for the dense network. The network lifetime remains steady at approximately 65%. However, the increase of grid size requires more supervisors to manage network, so the network lifetime slightly decreases if the grid size exceeds 150 m.

Since each STA has the constant awake time, the network lifetime in either IEEE 802.11 active mode or DAI protocol remains at 19.85 mins and 37.02 mins, respectively. Additionally, the network lifetime in the IEEE 802.11 PS mode markedly decreases with the increase of the grid size. We reason that the number of supervisors increases in the sparse network. Notably, such approach achieves the deteriorated performance when the grid size is 0 m. That’s because the collision of beacons is most likely appear in the network.

4.2.3 Network Synchronization

In the paper, the simulation about network synchronization focuses on the clock drift among the STAs, which enables a STA to be unaware of the time that other PS STA will awake up to receive the packet. We start to collect the clock drift between two STAs with the fastest and slowest clocks every beacon interval once all STAs form an IBSS. Then, the maximal value of these clock drifts, obtained from 10000 collections, is exploited to evaluate the performances of the IEEE 802.11 active mode and PSC-MAC.

As Figure 10 shows, PSC-MAC significantly outperforms the IEEE 802.11 active mode in all scenarios of different grid sizes. Notably, the scenario that all STAs are in a single-hop MANET (i.e., grid
size is 0m) obviously incurs significant clock drifts owing to frequent collisions. The problem is diminished when the grid size reaches 50m. However, numbers of clock drifts is dramatically generated as the grid size increases. That's because the number of STAs necessary to perform time synchronization increases. Each STA in the IEEE 802.11 active mode requires to become the controller and synchronize with the STA with the faster clock. In PSC-MAC, since more supervisors require to transmit their beacons at each TBTT, the clock drift obviously increases in the sparse network.

Unlike IEEE 802.11, which randomly selects some STAs as the controllers of the network, PSC-MAC efficiently determines the supervisors by means of the proposed rules. The simulation results shown in Figure 10 verify that PSC-MAC causes less clock drift compared to IEEE 802.11. Moreover, such precision in time makes PSC-MAC beneficial for packet broadcasting due to less retransmissions.

5 Conclusions

The proposed PSC-MAC is able to determine the suitable supervisors, formed a backbone of the network to manage the network in the passive manner due to less communication overhead. With the aid of the beacon interleaving approach, all supervisors in the supervising sets in turn transmit the beacons in different beacon intervals. Additionally, PSC-MAC dynamically change the roles of STAs according to their remaining battery power as the variation of the network topology. Simulation results also validate the that PSC-MAC outperforms IEEE 802.11 and the existing methods. Our future studies can investigate solutions, which can determine the supervisors by taking the other metrics such as network status and neighboring STAs information into account.

References


