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
Email: 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. PSC-MAC focuses on determining multiple supervising sets, each of which consists of some power-rich stations, supervisors*, to be in charge of the network management. Supervisor determination in PSC-MAC is achieved by a passive manner due to less communication overhead. The main idea of PSC-MAC is beacon interleaving, which guarantees that supervisors in different supervising sets transmit beacons in the different beacon intervals. The proposed rules, deficiency, isolation, and partition rules, enable each station to dynamically and passively transit its role to either a supervisor or a member. Simulation results show that PSC-MAC outperforms IEEE 802.11 and the previous research in terms of supervisor determination, clock synchronization, and energy efficiency.*

1. Introduction

A number of mobile stations (STAs) form an autonomous network, called *mobile ad hoc network* (MANET), in which a STA always communicates with its destined STA in a multi-hop manner. Thus, such network can be regarded as a multi-hop MANET (MH-MANET). In an MH-MANET, numerous important issues, such as clock synchronization, network partitioning, and energy efficiency should be considered in the design of the MAC protocol.

In IEEE 802.11, clock synchronization is achieved by a distributed *timing synchronization function* (TSF), tuning a STA's local timer when it hears a beacon [1]. The protocol proposed in [4] selects the STA with the faster clock to synchronize others via beacon transmissions, but the protocol limits to a single-hop MANET. Obviously, clock synchronization may not be achieved due to the absence of APs and inconsistent packet delay, incurred by unpredictable mobility and radio interference [5]. In principle, imprecise clock probably cause a STA in the power-saving mode (PS mode) failed in transmitting data because of the inconsistent awake/asleep schedules, so the STA is unaware of STAs within its radio range. Such incorrect neighbor information may incur the *network partitioning* problem, wherein the STAs, actually belonging to one IBSS may be partitioned into multiple IBSSs [5]. Additionally, numerous existing routing protocols require neighbor information during the route discovery phase. The route may be undiscovered in case of the incorrect neighbor information.

Unlike power-rich APs, STAs in MH-MANETs are limited in the battery power. IEEE 802.11 proposes the power saving mechanism (PSM) for energy conservation [1], but PSM is only designed for the single-hop network. Moreover, in IEEE 802.11, all STAs use a contention mechanism to transmit beacons. If a STA with less remaining energy always successfully transmits a beacon after random delay, such STA quickly consumes the battery power because of awakening during the whole beacon interval (hereafter referred as BI), and consequently fails to work.

In wireless networks, broadcasting is a communication pattern frequently used. *Flooding* is a well-known and widely used scheme due to its simplicity. However, the scheme is likely to generate the *broadcast storm problem*, mainly resulted from the contention, collision, and redundancy [3]. Although numerous approaches are proposed to resolve or alleviate such problem, sophisticated computation and hardware cost make these mechanisms complicated [6].

The paper proposes a passive self-configuration MAC protocol (PSC-MAC) to cope with the aforementioned problems in MH-MANETs. In PSC-MAC, a STA is self-determined in a passive and decentralized fashion to become a *supervisor*. The main idea of PSC-MAC is *bea-*

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con interleaving, by which two neighboring supervisors are inhibited from beacon transmissions in the same BI. All supervisors are consequently divided into multiple connected sets, called *supervising sets*. The STAs in an individual set only need to transmit beacons in the specific BI. Additionally, PSC-MAC exploits the *deficiency*, *isolation*, and *partition* rules for a STA to make a decision to become a supervisor.

Overall, PSC-MAC has significant advantages: (1) PSC-MAC incurs less communication overhead because supervisors are determined by means of a passive manner. (2) PSC-MAC is suitable for the variation in MH-MANETs with the characteristic of the self-configuration. (4) PSC-MAC increases the longevity of the network due to consideration of STAs' operation modes. (5) PSC-MAC relieves the broadcast storm problem with the aid of connected supervisors.

The rest of this paper is organized as follows. Section 2 formulates our network model and gives an overview of PSC-MAC. Section 3 then details the proposed PSC-MAC protocol. Meanwhile, the simulation results are shown in Section 4. Finally, Section 5 presents conclusions and future research directions.

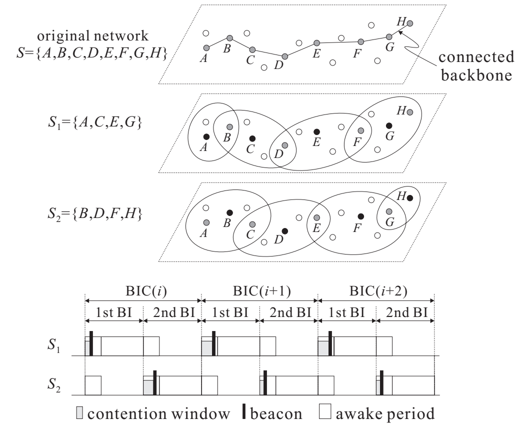

Figure 1. Overview of PSC-MAC. In the original network, the gray and white circles are respectively the supervisors and members. The dark circles form the supervising set in the corresponding BI. STAs A, C, E, and G form S_1, while STAs B, D, F, and H form S_2. Such behavior achieves beacon interleaving in each BIC.

2. Problem Description

The MH-MANET considered is represented as a simple graph $G = (V, E)$, where V and E represent the sets of mobile STAs and edges, respectively. An edge between STAs u and v is termed (u, v). All STAs are assumed to have the same radio range. Namely, if there exists an edge $e = (u, v) \in E$, it means that both STAs u and v are within the radio range of each other. Thus, the graph G can be viewed as an undirected graph.

Consider an MH-MANET, wherein some STAs, regarded as supervisors form a backbone. Non-supervisor STAs are members. A supervisor is responsible for beacon transmission, while a member only passively observes the network condition to make a decision to become a supervisor.

Based on the discussion addressed in Section 1, we conclude that a supervisor has to satisfy the properties: (1) A supervisor should have at least one neighboring supervisor. (2) Two neighboring supervisors should transmit beacons in different BIs. (3) A STA should be served by at least one supervisor in each BI. (4) A supervisor should be a power-rich STA.

In PSC-MAC, all STAs are divided into multiple sets. STAs in each set in turn wake up to transmit their beacons in different BIs in a Beacon Interleaving Cycle (BIC), which is defined as below.

Definition 1 *Beacon Interleaving Cycle (BIC) is a repeated period, composed of two or more beacon intervals for beacon interleaving.* □

The number of BIs in a BIC is denoted as N_{BI}, which is a system parameter, predetermined and well-known by all STAs. All BICs are in order represented by BIC(i), $i = 1, 2, ...$ Let S be a set of all supervisors, where $S \subseteq V$. Thus, all supervisors are divided into N_{BI} supervising set(s), one of which is termed S_i, $i = 1, 2, 3, ..., N_{BI}$.

Actually, PSC-MAC aims to finding a minimum number of STAs to play the roles of supervisors. However, such optimization problem belongs to NP-complete problem. In the paper, we concentrate on a distributed heuristic solution to supervisor determination.

Figure 1 shows an overview of PSC-MAC, where $N_{BI} = 2$. 8 STAs (i.e., STAs A, B, C, D, E, F, G, and H) are assumed to be determined to act as supervisors, so that the STAs form a connected backbone. Suppose $S = \{A, B, C, D, E, F, G, H\}$, regarded as a connected backbone in the network. All supervisors in S are divided into two supervising sets. Assume that $S_1 = \{A, C, E, G\}$, while $S_2 = \{B, D, F, H\}$. STAs in S_1 and S_2 are respectively responsible for beacon transmissions in the first and the second BIs. Note that, in the first BI, all supervisors in S_2 revoke the supervisor roles and become members since the network is controlled by supervisors in S_1. Similarly, all supervisors in S_1 should become members in the second BI since beacon transmissions are performed by all supervisors in S_2.

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3. Passive Self-Configuration MAC Protocol (PSC-MAC)

The section first describes beacon interleaving and then elaborates the rules for supervisor determination and withdrawal.

3.1. Beacon Interleaving

Recall that all supervisors in PSC-MAC are connected. If the individual supervisor transmits its beacon in a BI, there are numerous supervisors which need to keep awake for the whole BI. The scenario significantly causes some supervisors, which does not require keeping awaken still transmit their beacons. Thus, in the paper, we devise the beacon interleaving technique to inhibit the neighboring supervisors from transmitting beacons in the same BI.

Figure 2 shows the basic concept of beacon interleaving. Let $N_{BI} = 2$. STAs A and B, B and C, and C and D are assumed to be within the radio ranges of each other, respectively. Here, we focus on the first BI in BIC(i). Let t_A, t_B, t_C, and t_D denote the times at which STA A, B, C, and D attempt to transmit their beacons, respectively. Suppose $t_A < t_B < t_C < t_D$. STA A will become a supervisor since it receives no beacon in the BI. STA B will cancel its beacon transmission and become a member due to the receipt of the beacon from STA A. Similarly, because $t_C < t_D$, STA C will become a supervisor, while STA D will inhibit its beacon transmission once receiving the beacon from STA C. Thus, STAs A and C form S_1. In the second BI, STAs B and D will form S_2, whereas STAs A and C will give up their supervisor roles by using the proposed rules for supervisor determination and withdrawal. Note that a STA will become a supervisor or withdraw the supervisor role when the network has insufficient or too many supervisors, respectively. Significantly, beacon interleaving restrains two neighboring supervisors from beacon transmission in the same BI so as to balance the energy wastes of the supervisors.

3.2. Supervisor Determination

In PSC-MAC, a STA exploits the proposed rules, including the *deficiency*, *isolation*, and *partition* rules to dynamically become a supervisor. The rules are the main resolutions in terms of the following phenomena, resulted from the variation in the network.

1. Deficiency Phenomenon

   In Figure 3(a), suppose STA A is a member, and STAs B and C are neighboring supervisors. As Figure 3(b) shows, STAs B and C are assumed to transmit beacons in the first and the second BIs in BIC(i), respectively.

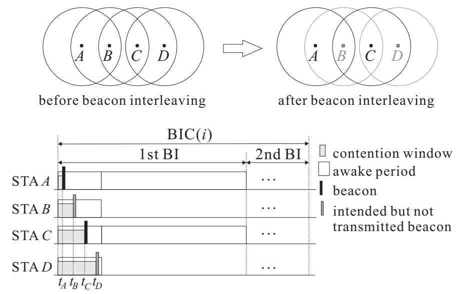

Figure 2. Basic concept of beacon interleaving.

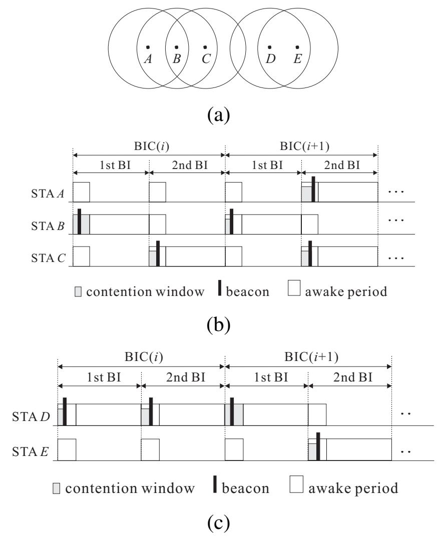

Figure 3. Deficiency and isolation rules. (a) network topology. (b) deficiency rule. (c) isolation rule.

   Obviously, STA A hears no beacon in the second BI in BIC(i) because it is a member and supervisor C is not within STA A's radio range. STA A should become a supervisor in the second BI in BIC($i + 1$) because of insufficient supervisors in the network. Thus, the deficiency rule is proposed as below.

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

   The rule is to guarantee that the network has enough supervisors to keep the network connected. By means of this rule, supervisors A, B, and C are consequently divided into two supervising sets. Namely, for example, $S_1 = \{B\}$ and $S_2 = \{A, C\}$ in Figure 3(b).

2. Isolation Phenomenon

   In Figure 3(a), suppose STAs D and E are respectively

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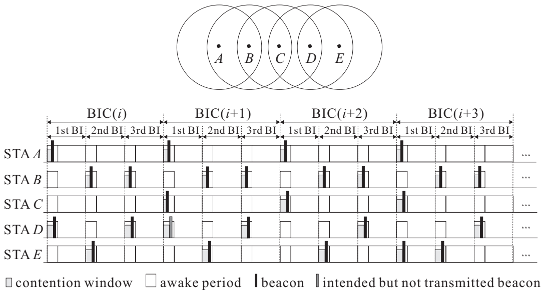

Figure 4. Partition rule.

a supervisor and a member. In BIC(i) in Figure 3(c), supervisor D is assumed to transmit its beacon in each BI so that STA E always receives the beacon from supervisor D in each BI. Obviously, STA D is regarded as an isolated STA due to no any neighboring supervisor. Although STAs D and E are able to receive beacons in the first and the second BIs of BIC(i), beacon interleaving of these STAs is not achieved. Therefore, the following isolation rule should be considered.

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

The rule is designed for the avoidance of consecutive beacon transmissions from the same supervisor in each BI. Under the consideration of this rule, in Figure 3(a), STA E will contend to become a supervisor in any one of BIs in BIC($i+1$). IF STA E successfully become a supervisor in the second BI in BIC($i+1$), beacon interleaving is obviously achieved.

3. Partition Phenomenon

Suppose, in Figure 4, STAs A, B, D, and E are supervisors, whereas STA C is a member. Let $N_{BI} = 3$. Supervisors A and D transmit beacons in the first BI, supervisors B and E transmit beacons in the second BI, as well as supervisors B and D transmit beacons in the third BI. Such scenario violates beacon interleaving in spite of enough supervisors in the network. Obviously, supervisors B and D will exhaust the energy quickly if STA C is always a member. Therefore, PSC-MAC employs the following rule to resolve the problem.

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

The partition rule largely targets to enable a STA within two non-neighboring supervisors to become a supervisor, so that these STAs can alternatively transmit beacons in different BIs. In BIC(i) in Figure 4,

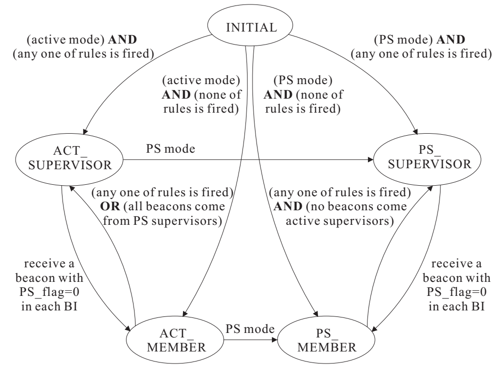

Figure 5. State transition diagram of a STA.

STA C perceives that it locates in the radio ranges of both supervisors B and D due to the receipts of beacons from the two supervisors in the third BI. The network is partitioned if STA C always inhibits from beacon transmission. By means of the partition rule, STA C will contend to become a supervisor in the first or the second BI in BIC($i+1$). Once STA C successfully becomes a supervisor in the first BI in BIC($i+1$), supervisor D will cancel its supervisor role in this BI. The behavior will cause STA E to receive no beacon in the first BI in BIC($i+2$). Thus, STA E needs to become a supervisor in the first BI of BIC($i+3$) according to the deficiency rule. Consequently, $S_1 = \{A, C, E\}$, $S_2 = \{B, E\}$, and $S_3 = \{B, D\}$ of BIC($i+3$).

In principle, the deficiency and partition rules are required for the formation and maintenance of a connected backbone. The isolation rule mainly concentrates on energy balance although the network still works without the aid of the rule. Based on the proposed rules, all STAs in the network are able to passively determine their roles and consequently achieve beacon interleaving.

3.3. Setup and Operation

Figure 5 illustrates the transitions among the states in PSC-MAC. Each STA is initially in the *INITIAL* state. Taking the role and operation mode into account, in addition to the INITIAL state, a STA will stay in the *ACT_SUPERVISOR*, *ACT_MEMBER*, *PS_SUPERVISOR*, or *PS_MEMBER* states. The ACT_SUPERVISOR and ACT_MEMBER states respectively represent the states of an active supervisor STA and an active member STA, while PS_SUPERVISOR and PS_MEMBER states represent the states of a PS supervisor STA and a PS member STA, respectively.

When a STA turns the radio on, it stays in the INITIAL state. Meanwhile, the STA enters the *setup phase*, comprising $N_{BI}+1$ BIs to observe the status of beacon interleaving, and then makes a decision to enter the corresponding states according to the operation mode and the proposed rules.

An ACT_SUPERVISOR STA periodically transmits beacons, but needs to enter the PS_SUPERVISOR state once entering the PS mode. If an ACT_SUPERVISOR STA hears beacons in all BIs, it has to enter the ACT_MEMBER state because there exist enough supervisors in the network. Like an ACT_SUPERVISOR STA, a PS_SUPERVISOR STA is also responsible for beacon transmission to temporarily maintain a connected backbone unless it hears a beacon from active neighboring supervisors. The PS_flag in the beacon issued from a PS_SUPERVISOR STA is set to 1 to inform other neighboring STAs its current operation mode.

Basically, a member regardless of its operation mode may become a supervisor once any one of the proposed rules is fired. An ACT_MEMBER STA requires entering the ACT_SUPERVISOR state if any beacon received come from PS_SUPERVISOR STAs to save the energy of these PS_SUPERVISOR STAs. A PS_MEMBER STA will enter the PS_SUPERVISOR state in case of no beacon coming from active supervisors.

4. Performance Evaluations

We conduct numerous simulations to evaluate the performance of PSC-MAC in terms of supervisor determination, energy efficiency, and clock synchronization.

4.1. Simulation Setup

In our simulation, 100 STAs are uniformly deployed in the network shown in Figure 6. The grid size, r, (i.e., the distance between two neighboring STAs) ranges from $0m$ to $250m$ with a step of $50m$. A slot time and a beacon interval are respectively $20\mu s$ and $100ms$. CW_{min} is set to 31. The ATIM window size is $20ms$. Let $N_{BI} = 6$. The transmission range and the initial energy of a STA is $250m$ and $100joule$, respectively. The energy consumption model used is the 2.4 GHz DSSS Lucent IEEE 802.11 WaveLAN card, whose power consumption of the transmit, receive, idle, and sleep states are $1327.20mW$, $966.96mW$, $843.72mW$, and $66.36mW$, respectively [2].

4.2. Simulation Results

Our simulation focuses on two factors, node density and mobility, to validate the performance of PSC-MAC. The variation of network density is simulated by changing the grid size of the network. Additionally, mobility is indicated by different network topologies, which is generated by randomly turning the STAs off with an interval of $500\mu s$.

1. Supervisor Determination

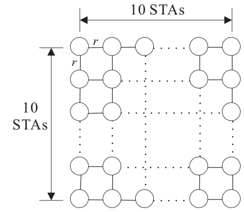

Figure 6. Grid network, each side of which has 10 STAs.

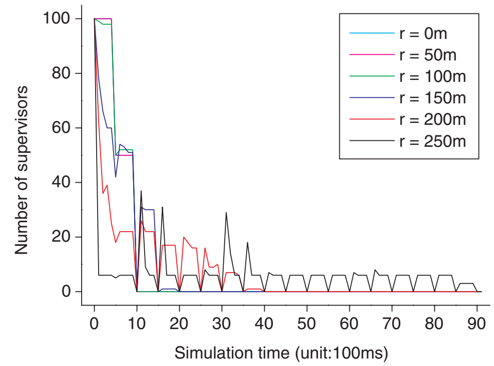

Figure 7. Variation in number of supervisors for different grid sizes.

PSC-MAC generates 6, 26, 63, 99, 100, and 100 supervisors in the networks with $r = 0m$, $50m$, $100m$, $150m$, $200m$, and $250m$, respectively. Obviously, more isolated STAs generate with the increase of grid size, so more supervisors are required in the network. As Figure 7 illustrates, PSC-MAC is able to quickly elect enough supervisors every $500ms$ so as to efficiently response to the variation in the network. Additionally, because the number of supervisors approximately keeps constant during the whole BIC. PSC-MAC is significantly reliable.

2. Energy Consumption

The number of alive nodes is used to evaluate the performances of different approaches in power consumption. Here, we consider the Dominating-Awake-Interval protocol (DAI) proposed in [5]. In Figure 8, the times, at which all STAs exhaust their energy, in PSC-MAC, 802.11 PSM, DAI, and 802.11, are approximately $80min$, $60min$, $40min$, and $20min$, respectively. PSC-MAC enables a STA to dynamically transit the role according to the proposed rules and the operation mode, so PSC-MAC outperforms other approaches in power consumption. In DAI, a PS STA

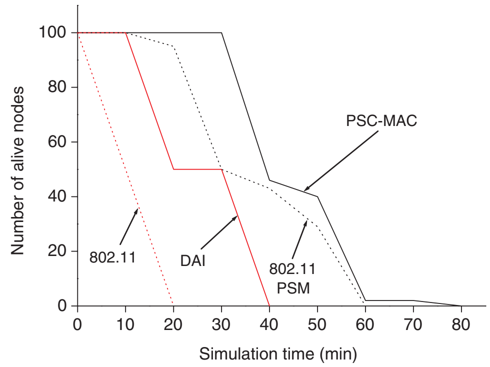

Figure 8. Simulation result of energy consumption.

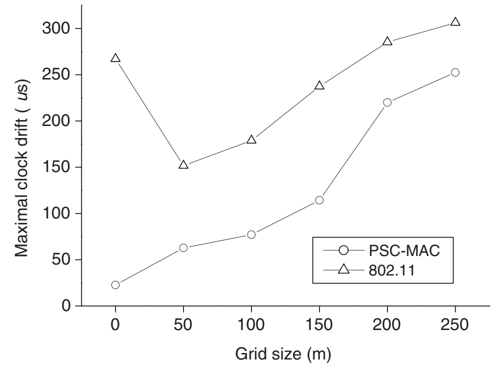

Figure 9. Simulation result of maximal clock drift.

should stay awake for at least about half of BI in each BI, so much power wastes compared to 802.11 PSM. Intuitively, the STA using 802.11 exhausts the energy quickly due to no sleep.

3. Clock Synchronization

   Clock synchronization, here, focuses on the clock drift among STAs. We start to collect the clock drift between two STAs with the fastest and slowest clocks every BI once all STAs are regarded into an IBSS. The maximal value of these clock drifts is determined from 10000 collections. In Figure 9, PSC-MAC outperforms 802.11 in all scenarios of different grid sizes. Unlike 802.11, which randomly and distributed selects some STAs as controllers, PSC-MAC efficiently determines the connected supervisors so as to incur less clock drift. Note that the scenario, where all STAs are in a single-hop MANET (i.e., $r = 0m$) obviously incurs significant clock drifts owing to frequent collisions. The problem is diminished when $r = 50m$. However, clock drift dramatically generates as the grid size increases. That is because the number of STAs necessary to perform clock synchronization increases.

5. Conclusions

In this paper, a novel passive self-configuration MAC protocol (PSC-MAC) is proposed to passively determine supervisors in IEEE 802.11-based MH-MANETs. Beacon interleaving motivates PSC-MAC to determine some supervisors, which form multiple supervising sets for beacon transmission in different BIs. Additionally, three rules are also devised to enable a STA to dynamically become a supervisor according to the beacons received. Our future studies can make an analytic model to validate the performance of PSC-MAC. More topologies and mobility models, including non-grid network and random waypoint mobility model will also be simulated.

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