Journal of Network and Computer Applications 56 (2015) 149–157

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

A passive self-configuration MAC protocol for supporting network management in IEEE 802.11-based multi-hop mobile ad hoc networks

Sheng-Shih Wang [a], Chun-Chih Li [b], Hsieh-Wei Lin [b], Kuei-Ping Shih [b,*]

[a] Department of Information Management, Minghsin University of Science and Technology, Xinfeng, Hsinchu, Taiwan
[b] Department of Computer Science and Information Engineering, Tamkang University, Tamsui, Taipei, Taiwan

ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form
30 April 2015
Accepted 25 May 2015
Available online 10 July 2015

Keywords:
IEEE 802.11
MAC protocol
Mobile ad hoc network (MANET)
Beacon interleaving

ABSTRACT

This paper proposes a fully distributed self-configuration media access control (MAC) protocol for IEEE 802.11-based multi-hop mobile ad hoc networks. The proposed MAC protocol targets to determine proper stations to become supervisors to support network management. This study first formulates the supervisor determination problem as the virtual backbone construction problem. Because determining the optimal number of supervisors falls into the NP-complete problem, this study uses many rules to determine enough supervisors to support network management. The determined supervisors are divided into multiple sets, and the supervisors in a set need to transmit beacon frames in the specific beacon interval. Using the proposed rules, not all the stations need to transmit beacon frames in each beacon interval. Moreover, the neighboring supervisors do not transmit beacon frames in the same beacon interval, thereby avoiding network partitioning, saving battery power, and achieving reliable broadcast. Simulation results confirm that the proposed MAC protocol actually determines enough and minimum number of supervisors. Results also show that the proposed MAC protocol leads to less packet collisions and reduces energy consumption, compared with the IEEE 802.11 standard.

1. Introduction

Mobile ad hoc networks (MANETs) are a collection of mobile nodes connected through wireless links. The fundamental MANET is a single-hop network, in which a node can communicate with each other (e.g., IEEE 802.11 ad hoc network). Due to the characteristic of limited radio range, communication between two nodes in some MANET applications must be achieved through a sequence of wireless links (i.e., in a multi-hop manner) (Hanzo and Tafazolli, 2009; Tseng et al., 2003; Wu et al., 2005; Zhang et al., 2013). This study calls this kind of MANETs the multi-hop MANET, denoted as the MH-MANET. In recent years, IEEE 802.11 has become a promising technology for a variety of MANET applications (IEEE Standard 802.11 Working Group, 2012). It specifies two operation modes: infrastructure mode and ad hoc mode. In infrastructure networks, access points are responsible for network management, such as clock synchronization, power management, and network connectivity. However, network management in ad hoc networks significantly becomes complicated for lack of access points. Because the IEEE 802.11 specifies the network operation in only a single-hop environment, stations (STAs) in IEEE 802.11-based MH-MANETs need a well-designed mechanism to support network management.

In IEEE 802.11-based MH-MANETs, clock synchronization is critical because it dominates the performance of many operations. Imprecise clock leads to an ineffective channel hopping in the frequency hopping technique, and it results in an inconsistent awake/sleeping schedule of STAs. This inconsistent schedule causes STAs in the power save mode failure in reception of data packets (Huang and Lai, 2002). It also causes a network partitioning problem, in which STAs are unaware of the existence of their neighboring STAs. Previous studies have proposed numerous mechanisms to achieve clock synchronization for single-hop networks (Huang and Lai, 2002; Zhou and Lai, 2005). Energy efficiency is also an important issue of network management in IEEE 802.11-based MH-MANETs, because battery power is a scarce resource for mobile STAs. To conserve STAs' power, IEEE 802.11 proposes a power management mechanism, which uses the announcement of traffic indication message (ATIM) window periods. Time in IEEE 802.11 is composed of consecutive repeated periods, called beacon intervals. Each STA wakes up at the target beacon transmission time (TBTT) of each beacon interval, and remains awake during the whole ATIM window period to contend for transmitting a beacon frame or listen for beacon frames from other STAs. However, this approach may suffer from a challenge in that low power STAs always successfully contend to transmit beacon frames, thereby quickly exhausting their residual power. In general, broadcast is one of the important transmission patterns for many applications, such as discovering routing paths to STAs

* Corresponding author.
E-mail address: kpshih@mail.tku.edu.tw (K.-P. Shih).

http://dx.doi.org/10.1016/j.jnca.2015.05.019
1084-8045/

(Abdelaziz and Elnainay, 2014; Johnson et al., 2007; Perkins et al., 2003; Qazi et al., 2013) and sending query messages to all STAs in the network (Helmy, 2004; Sadagopan et al., 2003). Although the fundamental approach, bind flooding, can achieve broadcast, it is not an efficient method to be used in MH-MANETs because this approach may cause redundancies, contentions, and collisions, collectively referred to the broadcast storm problem (Ni et al., 1999).

The solution to network management in MH-MANETs can be concluded that selecting proper STAs to form a connected virtual backbone, and the STAs of the backbone cooperatively transmit beacon frames to achieve clock synchronization, prevent network partitioning, reduce energy consumption, and avoid the broadcast storm problem. A number of state-of-the-art studies have proposed many strategies to the determination of proper nodes to form the virtual backbone (An et al., 2007; Heinzelman et al., 2000; Younis and Fahmy, 2004; Yu et al., 2013; Zhang et al., 2012). Existing studies have also proposed numerous backbone construction mechanisms (Alzoubi et al., 2002; Cheng et al., 2006; Leu and Chang, 2012; Min et al., 2004; Torkestani, 2013). All the proposed mechanisms operate above the MAC sublayer and assume that a well-designed MAC protocol is provided. However, this assumption is not always true, especially when reliable links are unavailable due to clock drift and collision. If handling the issues of network management at the lower layer, the above assumption can be released and the tasks of the upper layer can be simplified.

This paper proposes a passive self-configuration MAC protocol, called PSC-MAC, to support network management in IEEE 802.11-based MH-MANETs. The main objective of PSC-MAC is to determine proper STAs, called supervisors, to transmit beacon frames from the viewpoint of the MAC sublayer instead of the logical link control sublayer. PSC-MAC uses a beacon interleaving strategy to inhibit the neighboring supervisors to transmit beacon frames in the same beacon interval. In PSC-MAC, time is composed of consecutive repeated periods, called beacon interleaving cycles (BICs). Each cycle consists of a fixed number of beacon intervals. To reduce the amount of control overhead, each STA in PSC-MAC uses a passive manner to determine whether it must become a supervisor in a BIC (i.e., STAs only passively hear the received beacon frames to make the decision). The determined supervisors form a virtual backbone, and they are divided into multiple supervising sets. The STAs in a specific supervising set must wake up to transmit beacon frames in the same beacon intervals of BICs. In a beacon interval, the STAs which transmit beacon frames are called the active supervisors, and non-active supervisors are called the dormant supervisors. Because determining a minimum number of supervisors is an NP-complete problem, this study introduces many rules to determine proper STAs to act as supervisors to provide clock synchronization, network connectivity, as well as energy efficiency. To our best knowledge, this study is the first to investigate the management issue of IEEE 802.11-based MH-MANETs from the viewpoint of the MAC sublayer. The advantages of the proposed PSC-MAC are fourfold: (1) The PSC-MAC generates a low communication overhead because of using a passive manner to determine supervisors. (2) The PSC-MAC extends the network lifetime and alleviates the broadcast storm problem because not all the supervisors need to transmit beacon frames in each beacon interval. (3) The PSC-MAC reduces the topology change because the determined supervisors are always the power-rich STAs. (4) The PSC-MAC is fully backward compatible with the legacy IEEE 802.11 standard.

The rest of this paper is organized as follows. Section 2 presents the network model and formulates the supervisor determination problem. Section 3 presents the proposed PSC-MAC in detail. Section 4 shows the performance evaluation results, and finally, Section 5 provides concluding remarks.

2. Preliminaries

This section presents the proposed network model and formulates the supervisor determination problem.

2.1. Network model

The MH-MANET considered in this study is represented as a simple undirected graph $G=(V,E)$, where V is the set of STAs and $E \subseteq V \times V$ is the set of direct links between two STAs. Denote the link between STA u and STA v as $e_{(u,v)}$, where $e_{(u,v)} \in E$. Let N_s be the number of STAs in the network. Assume that all STAs have the same communication range. If STA u and STA v are within the communication ranges of each other, STA v is said to be the neighboring STA of STA u, and vice versa. Recall that PSC-MAC determines proper STAs to act as supervisors and divides these determined supervisors into multiple supervising sets. Non-supervisors in PSC-MAC are called the members. STAs in a supervising set need to transmit beacon frames in the certain beacon intervals of each BIC. Indicate the i-th BIC as BIC_i, where $i>0$. Let N_{BI} denote the number of beacon intervals in a BIC. The N_{BI} is a pre-determined system parameter and known by all STAs. Denote the k-th beacon interval of BIC_i as $BI_i(k)$, where $k=1,2,\dots,N_{BI}$. The supervisors in a BIC are divided into N_{BI} supervising sets. Let $S_i(k)$, where $k=1,2,\dots,N_{BI}$, denote the set of supervisors that must transmit beacon frames in $BI_i(k)$.

2.2. Problem statement

This study uses the following variables to formulate the supervisor determination problem. Define a 0–1 variable, $x^{nbr}_{(u,v)}$, to indicate whether STA u and STA v are neighboring STAs in a BIC. This variable is defined as

$$x^{nbr}_{(u,v)} = \begin{cases} 1 & \text{if } e_{(u,v)} \in E\ , \\ 0 & \text{otherwise.} \end{cases}$$

Use a 0–1 variable to indicate the status (active or dormant) of a supervisor in a beacon interval. We define this variable as

$$s^{act}_u(k) = \begin{cases} 1 & \text{if STA } u \text{ is an active supervisor in the } k\text{−th beacon interval,} \\ 0 & \text{otherwise.} \end{cases}$$

Given a pre-determined system parameter, denoted as ρ, to indicate the threshold of the remaining power. If the remaining power of a STA exceeds ρ, the STA is in the high power status; otherwise, the STA is in the low power status. Define a 0–1 variable, $s^{pw}_u(k)$, to indicate the power status of STA u in the k-th beacon interval of a BIC. It is defined as

$$s^{pw}_u(k) = \begin{cases} 1 & \text{if STA } u \text{ is in a high power status in the } k\text{−th beacon interval,} \\ 0 & \text{otherwise.} \end{cases}$$

This study aims to determine proper supervisors to construct a dynamic virtual backbone at the MAC sublayer. The supervisors the proposed PSC-MAC determines have to satisfy the following properties.

Property 1. *A STA must have at least one neighboring active supervisor in a beacon interval.*

The main goals of this property are to guarantee that the virtual backbone formed by determined supervisors is connected, to diminish the clock drift between STAs, and to alleviate the broadcast storm problem. We formulate this property as

$$\sum_{u,v \in V, x^{nbr}_{(u,v)}=1, s^{act}_u(k)=0} s^{act}_v(k) \geq 1, \quad \forall k=1,2,\dots,N_{BI}.$$

Property 2. *The neighboring supervisors cannot become active in the same beacon intervals.*