Lei and Rhee *EURASIP Journal on Wireless Communications and Networking* (2016) 2016:26
DOI 10.1186/s13638-016-0524-5

EURASIP Journal on
Wireless Communications and Networking
a SpringerOpen Journal

RESEARCH Open Access

Improving the IEEE 802.11 power-saving mechanism in the presence of hidden terminals

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Abstract

Due to its low cost and popularity, the IEEE 802.11 WLAN (wireless local area network) is considered as one of the most promising wireless technologies for IoT (Internet of Things). 802.11 WLAN also provides a PSM (power saving mechanism), by which the devices that have no data to transmit are enabled to turn into doze mode where much less power is consumed. However, the 802.11 PSM is known to be inefficient because of its contention-based mechanism, i.e., it suffers from the performance degradation due to hidden terminals, especially in a network with a large number of devices. In this paper, in order to improve the performance of the 802.11 PSM, we propose a BC (backoff counter) reservation scheme that is combined with a neighbor polling solution. By building analytic models and performing extensive simulations, we show that our proposed scheme provides a much improved performance.

Keywords: Internet of things, 802.11 Power saving mechanism, Backoff counter reservation, Hidden terminals

1 Introduction

IoT (Internet of things) is considered as a technological revolution in computing and communications [1]. In the vision of IoT, almost every thing, asset, and object in the world can communicate with each other directly through the equipped network interfaces or the embedded sensors [2, 3]. With a tremendous amount of heterogeneous things connected to the Internet, the realization of IoT is expected to bring in various technical challenges [4]. In particular, since most of the IoT devices are battery-powered, energy efficiency is required as the prerequisite to the networking protocols for IoT.

Nowadays, due to its low cost and popularity, the IEEE 802.11 WLANs (wireless local area networks) are adopted by most of today's electronic mobile devices. WLANs can offer cost savings and facilitate faster deployments [5, 6]. Also, they can provide high throughputs and high transmission rates that are required by some sensors today, such as those used in seismic monitoring and imaging. Thus, the WLAN technology is considered as one of the most promising wireless technologies for IoT [7].

In 802.11 WLANs, devices can be deployed in ad hoc mode, where devices can communicate with each other without a base station. Also, in order for power conservation, 802.11 MAC (media access control) provides a PSM (power saving mechanism), by which the devices can turn off their radios and stay in doze mode for power saving after a certain period of idle state [8]. The devices can buffer traffic for a certain period if the destination devices stay in doze mode, and during ATIM (announcement traffic indication message) window, all the devices become active for ATIM frame transmissions. When the ATIM window terminates, the devices having received or successfully transmitted an ATIM frame keep awake in the remaining BI (beacon interval) for data transmissions, while others enter into doze for power conservation.

However, the 802.11 PSM scheme suffers from performance degradation in densely deployed networks, such as in IoT environment. First, because 802.11 MAC is a contention-based mechanism, the heavy contentions among devices for limited channel resource can result in long access delay and collision [9]. Second, devices can randomly choose the same BC (backoff counter) according to 802.11 DCF (distributed contention function), which brings in transmission collisions. He et al. [10] has investigated this drawback, and presents an

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SRB (semi-random backoff) method. In SRB, devices are allowed to set their BC to a deterministic value upon a successful packet transmission. By reusing the BC of the previous successful transmission, SRB effectively prevents the devices from selecting a same BC. Furthermore, because 802.11 MAC is a CSMA/CA (carrier sense multiple access/collison avoidance) scheme, hidden terminals exist in 802.11 WLAN. Especially in a densely deployed network, hidden terminal effect can introduce high collision probability.

We use Fig. 1 to explain the hidden terminal problem. Here, device *B* locates at the transmission range of both devices *A* and *C*, while devices *A* and *C* are outside each other's transmission range. Thus, a transmission from device *A* or *C* can be received by *B*, but *A* and *C* cannot overhear each other. When device *A* starts a transmission, since device *C* cannot sense that, *C* may start a transmission at the same time, consequently, a collision occurs at *B*. In summary, the above drawbacks in 802.11 MAC make the devices try to retransmit and thus wastes mounts of power.

In this paper, we are concerned about improving the 802.11 PSM in the environment of IoT. The main contributions of this paper are

(1) We suggest a BC reservation scheme for devices to reduce the probability of randomly choosing the same BC. Based on the proposal, devices which have successfully transmitted a control frame, ATIM frame, can reserve a BC by that frame, and the following data transmissions are proceeded using the reserved BC. The difference between our approach and [10] is that our approach targets on enhancing 802.11 PSM, while SRB method in [10] works on the top of 802.11 DCF/EDCA (enhanced distributed channel access).

(2) We present a neighbor polling scheme for mitigating hidden terminal effects. As the wireless transmission has a broadcast feature, an ongoing transmission collided with a transmission from a hidden terminal can be overheard by the devices located at the transmitter's transmission range. We name these kinds of devices as neighbors of the transmitter in our proposal, and we enable one of the neighbors to poll the transmitter to transmit once again, by using the neighbor's ongoing transmission. Since our solution is totally distributed, the computational load of the network will not increase.

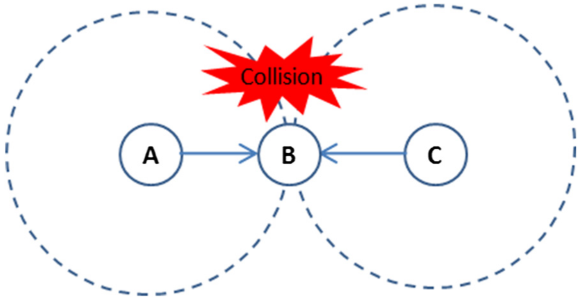

Fig. 1 Hidden terminal problem

The remainder of this paper is organized as follows. Section 2 presents an overview of the 802.11 PSM, which is followed by the related works on the power-efficient protocols. Section 3 describes the details on our proposed scheme, and Section 4 is devoted to building analytical models for performance evaluation. Extensive simulations are conducted in Section 5, and concluding remarks are drawn in Section 6.

2 Preliminary

2.1 IEEE 802.11 DCF

In the IEEE 802.11 DCF, a device should sense the channel for a period of DIFS (DCF inter frame space) before its transmission [11]. Only if the channel continually keeps idle for DIFS, the device can access the channel for transmission. Otherwise, as depicted in Fig. 2, the device enters into a backoff procedure by randomly choosing a value from $[0, w]$ as its BC, where w is the value of the device's current contention window. The 802.11 standard has defined the minimum and maximum values of the contention window (CW_{min}, CW_{max}). The initial value of a device's contention window is CW_{min}, and this value will be duplicated in case the device experiences a collision; otherwise, if a transmission is successful, the value will return to CW_{min}. On the other hand, when the device's contention window reaches to CW_{max}, the device has to sustain the value even if it encounters another collision.

While staying in backoff procedure, the device continues to sense the channel, and as soon as an idle channel is sensed, the device starts to reduce its BC for one time slot. When the BC of the device reaches 0, the device can start its transmission immediately.

2.2 IEEE 802.11 PSM

In order to improve the power efficiency, 802.11 MAC has proposed a PSM to allow devices without data for transmission to enter into the doze mode, where quite less power is consumed. In ad hoc mode, the 802.11 PSM works in a distributed fashion. Devices autonomously construct an IBSS (independent basic service set), and the time is divided into BIs (beacon intervals). All the devices belonging to the same IBSS are timely synchronized and share the same BI and TBTTs (target beacon transmission times). During a BI, when the TBTT starts, devices contend to deliver a beacon frame, and if one device successfully delivers a beacon, then other devices cancel the pending beacon transmissions and adjust their clocks in

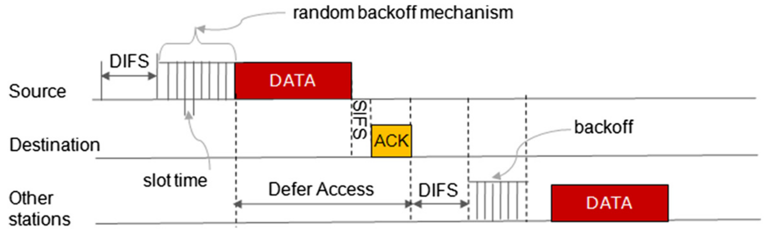

Fig. 2 IEEE 802.11 DCF

accordance with the time stamp stored in the beacon. Following the TBTT, an ATIM window is initiated, during which all devices stay in active, and those devices that have data frames buffered for others contend to transmit ATIM frames. When the ATIM window terminates, only the devices that have successfully transmitted or received ATIM frames keep active for data transmissions, and other devices can enter into doze mode until next BI.

Figure 3 illustrates the work procedure of 802.11 PSM. Here, devices *A*, *B*, and *C* belong to the same IBSS. In the first BI, as device *A* has frames buffered for device *B*, it delivers an ATIM frame during the ATIM window. Receiving the ATIM frame, device *B* keeps active after the termination of the ATIM window. Thus devices *A* and *B* can exchange data frames in the following BI. On the other hand, as device *C* has not received any ATIM frames during the ATIM window, it immediately enters into the sleep mode. During the second BI, all the devices keep active in the ATIM window again. As none of them have traffic buffered for others, ATIM frames are not delivered, and after the ATIM window, all the devices enter into doze mode.

However, the PSM for ad hoc mode does not work efficiently in a congested network: the heavy contentions for channel access can run down device's power quickly, and especially in a large size network, a big part of power is consumed for channel contention. Furthermore, hidden terminals can cause transmission collisions and result in high power consumption as well as decrement of the network performance.

2.3 Related works

Various approaches have been proposed for improving the power efficiency of wireless devices. Vukadinovic et al. [7] present a traffic announcement solution to enhance the 802.11 PSM for multi-hop ad hoc networks. Because when a data frame is forwarded over multiple hops, only the next hop device is notified about the pending frame, devices on other hops may stay in doze mode and thus causes quite a long end-to-end delay. Proposed scheme enables each device along the routing path to send a traffic announcement to its downstream neighbor in advance. As a result, the data frames can be forwarded over multiple hops in a single beacon interval, and the end-to-end delay in the multi-hop transmission is decreased efficiently.

In [12], mobile devices are enabled to work cooperatively to take advantage of the good channel quality of SR (short range) links for reducing transmission time and reserving power. The nearby devices form a cluster, and a cluster head is selected to relay traffic for devices. Instead of transmitting data to AP (access point)/BS (base station) directly using the LR (long range) communication technology, the devices deliver their data traffic to the cluster head using SR communication technologies, such as 802.11 WLAN. Then, the cluster head can relay the traffic to the AP/BS on behalf of other devices, using the LR communication technology, such as WiMax.

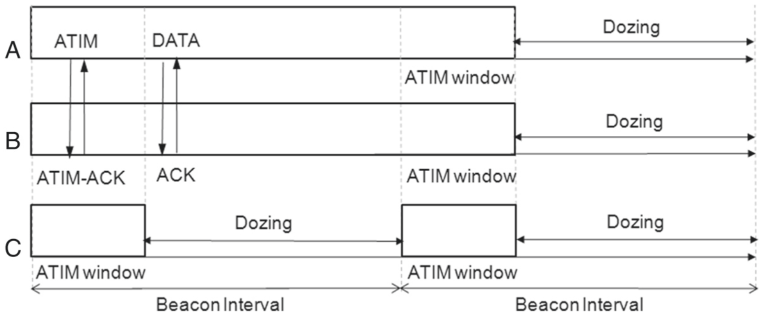

Fig. 3 PSM procedure in an ad hoc IBSS consisting of 3 devices A, B and C

In [13] a power-saving protocol for reducing power, consumption of APs is presented. This approach allows AP to enter into doze mode when it has no traffic for transmission during a period of time. Devices can convey wake-up signals to AP by the equipped wake-up transceivers. This approach decreases the power consumption of APs by decreasing the time spent in idle state. These approaches mentioned above, however, cannot be adopted for IoT communication effectively; [12] focuses on enabling the implemented wireless interfaces to work adaptively, while power efficiency for each wireless interface is still unsolved. Also, [13] requires new radios to be equipped with devices, and additional solutions for managing the operation of the radios are also needed.

Lin et al. [14] point out that in infrastructure mode, wireless devices waste their powers on idle state, as the devices should continually sense channel and overhear the ongoing transmissions of the other devices. Also, the contentions among devices waking up at the same moment for traffic retrieval can cause power waste. The authors provide a DeepSleep scheme to enhance the 802.11 PSM for energy-harvesting devices, where the devices short of power can enter into doze mode for a long period and then access the channel with a higher priority. In order to avoid a large number of devices waking up at the same moment, a random deferring algorithm is applied to randomly defer the wake up time of devices, which can alleviate the channel contentions among devices.

He et al. [15] propose a TDMA (time division multiple access)-based MAC protocol for decrement of contentions among 802.11 devices. A BI is divided into a number of equal time slices by an AP, and the slices are allocated to single devices or groups of devices. Therefore, instead of contending for channel access, each device wakes up in its allocated time slot for data retrieving. This method effectively reduces energy consumption of PSM devices by removal of channel contention. The problem is, if a PSM device does not wake up in its time slot, the allocated channel resource will be wasted. Also, as all the time slots have the same length without considering frame length or traffic load, the allocated time slots may be inefficiently used in case of short frames or light traffic.

Because the fixed ATIM window can degrade the performance of PSM, Eun-Sun et al. [16] propose an IPSM (improved power saving mechanism) to adaptively tune the size of ATIM window. When a certain period of idle channel is sensed during the predefined ATIM window, devices can terminate the ATIM window and start to transmit data frames. Otherwise, if the current period of ATIM window is too short, devices can dynamically enlarge the window size for a certain scale. While this protocol can efficiently enhance the performance of 802.11 PSM, it lacks a solution for a hidden terminal problem.

3 Improving 802.11 PSM

In this section, we describe our proposal, a BC reservation scheme that is combined with a neighbor polling method for improvement of 802.11 PSM in the IoT environment. The key idea is as follows: since all the devices keep active during the ATIM window and an on-going transmission can be overheard by all other devices, a device can utilize its ongoing ATIM frame to reserve a BC. Then, after the ATIM window terminates, the devices can transmit their data by using reserved BCs. This method can reduce the idle channel resulted from the large values of BCs and eliminate the collisions caused by identically chosen BCs. Also, in order to mitigate the hidden terminal problem, a neighbor polling method is employed, by which a device which failed in ATIM frame transmission is allowed to have an opportunity for delivering an ATIM frame to reserve a BC.

3.1 BC reservation

The details of the proposed BC reservation scheme are as follows. Each device keeps a table for recording the reserved BCs of all devices in the same IBSS. During the ATIM window, a device that first delivers an ATIM frame will be recorded into the first entry of the BC table. The first device acknowledges other devices that it has reserved 1 as its BC. In the same way, at the end of the ATIM window, all the devices having transmitted ATIM frames can reserve a BC based on the orders of their transmissions. In order to make sure that all the devices have a same BC table, right after the ATIM window, the device which has sent a beacon frame broadcasts a short message with the information on reserved BCs once again.

In order to prevent CAM (continuous active mode) devices from contending with PSM devices, the minimum contention windows of CAM devices are set to $CW_{min} + offset$, where CW_{min} is the initial minimum contention window (usually equals to 15 or 31) defined in 802.11 MAC, and the offset is the largest BC plus one (this modification is made in order to set the BCs of CAM devices with larger values than all PSM devices). The initial BCs of CAM devices are randomly chosen from $[CW_{min} + offset, 2(CW_{min} + offset)]$.

When the ATIM window terminates, all the active devices start to sense channel for a period of DIFS, and then enter into the backoff process. One time-slot later, the device with $BC = 1$ completes its backoff procedure and starts to transmit data. If several frames are buffered, the device can continually occupy the channel by setting the *More Data* field of the ongoing frame as 1, and the duration field as the period of time for current transmission plus one more transmission. After the device delivered all the buffered frames, the device itself and the destination device should confirm whether they have received ATIM frames from each other. If

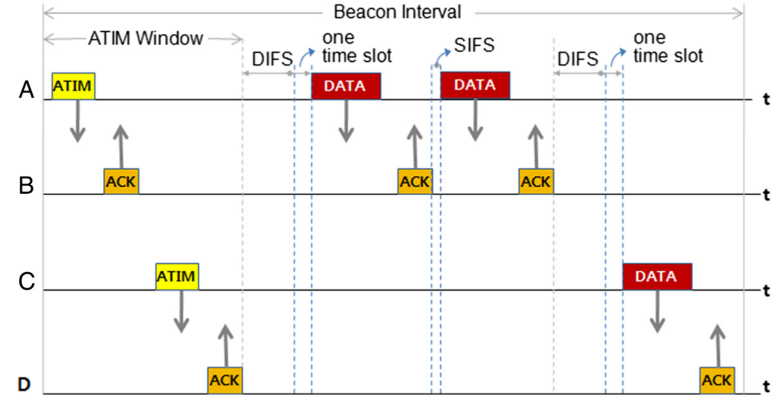

Fig. 4 Devices A, B, C and D transmit under the proposed scheme

they have received the frames, those devices should stay active continually; otherwise, they enter into doze mode immediately.

In case a device dose not transmit (moves out or looses synchronization) in its reserved time slot, all the other devices decrease their BCs by one. After the time slot, the device having reduced its BC to 0 can start to transmit. On the other hand, if a PSM device has not transmitted a frame successfully within its reserved BC, it should randomly choose a BC in the same way as the CAM devices, and try to retransmit after the reserved period completes.

Figure 4 illustrates the detailed transmission process of the BC reservation scheme. In the figure, after an ATIM window terminates, each device has reserved a BC and the reserved BCs are the same as Table 1. After the ATIM window, the BC of device *A* reduces to 0 after DIFS period plus one time slot, and device *A* starts to transmit. As two frames are buffered for device *B*, device *A* sets the *More Data* field of the first frame to be 1, and the duration field as the period for transmitting current frame plus another frame. Then after the first frame, device *A* can continue to deliver the second frame SIFS (short inter frame space) time later. When device *A* has transmitted all the buffered frames, both devices *A* and *B* enter into the doze mode. And DIFS plus one time slot later, the BC of device *C* reaches 0, and *C* starts its transmission. The CAM devices, having set their BCs with large values, can access the channel after the reserved sequences terminate.

Table 1 BC table

Sender ID	Receiver ID	BC
A	B	1
C	D	2

3.2 Neighbor polling for hidden terminal

Since the proposed BC reservation scheme is based on CSMA/CA, hidden terminals in the network may cause performance problems. We reuse Fig. 1 to explain how the hidden terminals affect the performance of proposed scheme, here, devices *A* and *C* are hidden terminals to each other. When device *A* transmits an ATIM frame to *B*, as device *C* which cannot sense the transmission may deliver an ATIM frame to *B* at the same time, a collision occurs in *B*, and both devices *A* and *C* cannot reserve a BC.

According to [17], in order for the ATIM frame sent from device *A* to be successfully received by *B*, *C* must hold its transmission for a vulnerable period T_v, where the duration of T_v is 2(ATIM+SIFS). One can find that from Fig. 5, if device *A* starts to send an ATIM frame to *B* at $t = 0$, then a transmission from *C* starts at any point in the interval $[t_1, t_2]$ will cause a collision at *B*.

Now, a simple neighbor polling scheme is applied to reduce the effects from hidden terminals. Because of the broadcast nature of 802.11 MAC, a transmission can be

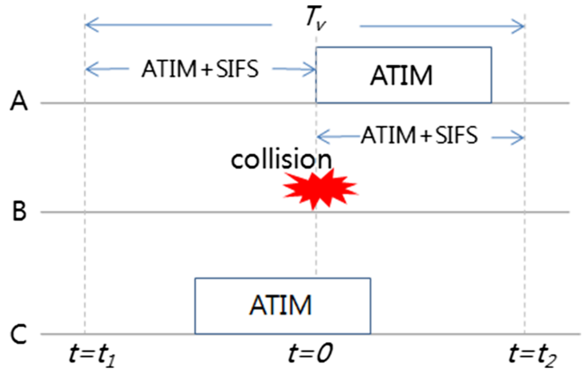

Fig. 5 The vulnerable period T_v for the ATIM frame delivery of devices A and C, while collisions may occur at B

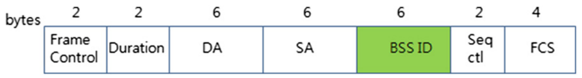

Fig. 6 ATIM frame

received by all the other devices located in the sender's transmission range. In this paper, we refer these devices as the neighbors of the transmitter. Hence, when a transmission experiences collision, the neighbor devices which locate in the transmission range of both the sender and receiver can monitor the unsuccessful transmission. We propose to let one of such neighbor devices poll the sender for transmitting once again, using its ongoing transmission. We use PATIM frame for the polling, which is a modification of the ATIM frame. As the BSS ID field of ATIM frame (Fig. 6) is usually not in use, we utilize the field to include the address of a polled device and denote the frame as PATIM frame.

Figures 7 and 8 depict the work procedure of proposed neighbor polling scheme. In the IBSS given by Fig. 7, devices A and C are hidden terminals to each other, while E is a neighbor to both B and C. When an ATIM frame from C to B fails because of A's transmission, device E can receive the ATIM successfully. If an ACK from B is not received, E can infer that C's transmission fails, and E records C into its Failure Transmission table.

As presented in Fig. 8, when device E accesses the channel, it delivers a PATIM frame to D with the BSS ID field being the address of C, and the duration field being $2(ATIM + SIFS) + ACK$ which is a period that device E successfully exchanges an ATIM with D, plus SIFS later C delivers an ATIM frame. Devices overhearing the ATIM set their NAVs the same as the duration field and refrain from transmitting. After device D delivered an ACK to E and SIFS later, C starts to transmit an ATIM frame. Then, through the ACK frame delivered by B, E confirms that C and B have successfully exchanged an ATIM, and it removes the record of C from its table. The polling from E enables C to reserve a BC that is one time slot larger than E's. Table 2 contains the values of BCs reserved by the devices.

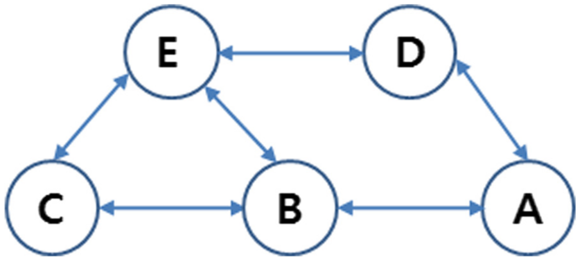

Fig. 7 A simple IBSS

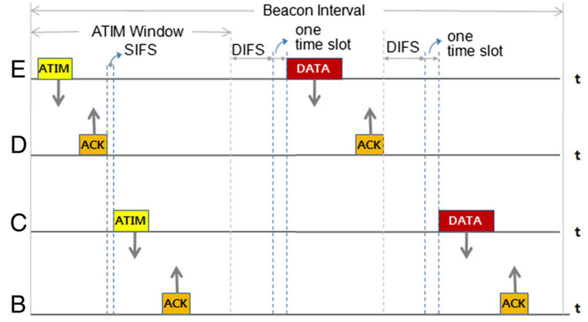

Fig. 8 Transmission process in neighbor polling scheme

The purpose of the neighbor polling scheme is not to reduce the collision probability resulted from hidden terminals, but to increase the transmission opportunity of a device. Because a hidden terminal to the polled device can overhear the ATIM (or ACK) frame from the neighbor device, the scheme prevents it from transmitting during the vulnerable period of the polled device. Note that, by sending an ATIM frame through polling, a device can reserve a BC successfully.

4 Performance analysis

A mathematical model for evaluating the performance of the proposed scheme is developed in this section. In order to study the average media access delay, as well as the power consumption, an IBSS constructed by n PSM devices is modeled, assuming no hidden terminals.

4.1 Media access delay

The model for studying the media access delay is borrowed from [18]. When a tagged device i senses channel, the channel can be in one of the following three possible events: $E_i = \{idle\ channel\}$, $E_c = \{collision\}$, and $E_s = \{successful\ transmission\}$, where E_i, E_c, and E_s are mutually exclusive. Denoting the transmission attempt probability of a device as p, the probabilities of these events are as follows:

$$\begin{aligned} P_i &= Pr\{E_i\} = (1-p)^{n-1} \\ P_s &= Pr\{E_s\} = (n-1)p(1-p)^{n-2} \\ P_c &= Pr\{E_c\} = 1 - P_i - P_s. \end{aligned} \tag{1}$$

Also, in basic DCF, the duration of a successful transmission is

$$T_S = T_{PHY} + E[P]/R + T_{ACK} + SIFS + 2\delta, \tag{2}$$

Table 2 BC table

Sender ID	Receiver ID	BC
E	D	1
C	B	2

and the duration for a collided transmission is

$$T_C = T_{PHY} + E[P]/R + \delta. \tag{3}$$

Before the device i reduces its BC for one slot, several transmissions from other devices may occur, which are either successful or not. If N is a random variable measuring the number of the transmissions, then T_{slot} time required by the PSM device to reduce the BC by one, is given by

$$T_{slot} = \sum_{k=1}^{N} T_w^k + t_{slot}, \tag{4}$$

where t_{slot} is the time period for one slot, T_w^k is transmission period of device k. Then, the average value of T_{slot} is

$$E[T_{slot}] = E[N]\,E[T_w] + t_{slot} = \frac{1-(1-p)^{n-1}}{(1-p)^{n-1}} E[T_w] + t_{slot}, \tag{5}$$

where $E[T_w]$ equals to

$$E[T_w] = P_s T_s + P_c T_c. \tag{6}$$

Now, let *X (CW)* be the value chosen by device i as the backoff interval when the contention window size is CW, then we can derive $E[T^{bo}(CW)]$, the average duration that i spent in backoff process, is as

$$E[T^{bo}(CW)] = E[X(CW)]\,E[T_{slot}] = \frac{CW-1}{2} E[T_{slot}]. \tag{7}$$

Therefore, we can find the MAC delay for the device i, giving the device successfully transmitted a frame after tried m times:

$$\begin{aligned} T_{legacy}^{MAC} = {} & DIFS + \sum_{j=1}^{m+1} T^{bo}(CW_j) \\ & + \sum_{j=1}^{m} T_j^{coll} \frac{(1-(1-p)^{n-1})^m (1-p)^{n-1}}{(1-(1-p)^{n-1})^{MAX}}. \end{aligned} \tag{8}$$

In our proposed scheme, if the tagged device has reserved i as its BC, then it can access channel after the foregoing *i-1* devices complete their transmissions. The average media access delay for the tagged device is given by

$$\begin{aligned} T_{proposed}^{MAC} & = \frac{\sum_{i=1}^{n} i(DIFS + t_{slot}) + \sum_{i=1}^{n}(i-1)T_s}{n} \\ & = \frac{n+1}{2}(DIFS + t_{slot}) + \frac{n}{2} T_s. \end{aligned} \tag{9}$$

If no collision is assumed in the transmission, (8) can be simplified as

$$T_{legacy\_sim}^{MAC} = \frac{n+1}{2}(DIFS + CW_{min}) + \frac{n}{2} T_s, \tag{10}$$

where the CW_{min} is the minimum contention window size. Combining with the parameters given by Table 3, we can find from Fig. 9 that the average delays of both schemes closely relate to the number of devices, i.e., the less the number of devices, the lower the overall delay of network is. Also it should be noted that our proposed scheme introduces much lower delay compared to the legacy PSM. The performance gain in our proposed scheme is due to the reduction of the BCs and the alleviation of the collisions among devices.

4.2 Power consumption

Now we build an analytic model for the power consumptions in both legacy and proposed scheme in this subsection. In order for simplicity, we assume in the legacy PSM, the contention windows of devices are set to the minimum value (CW_{min}), and there is no collision or channel error. We denote the power consumption for transmission as P_{tx}, for reception as P_{rx}, and for idle state as P_{idle}.

During an ATIM window, a device keeps active continually for ATIM transmissions, and the power consumed for delivering an ATIM frame is

$$E_{ATIM} = P_{tx} \times T_{ATIM} + P_{rx} \times T_{ACK} + P_{idle} \times SIFS. \tag{11}$$

The power consumed by a device in a whole ATIM window can be calculated as

$$\begin{aligned} E_{ATIM\_window} = {} & E_{beacon} + E_{ATIM} \\ & + P_{idle} \times (T_{ATIM\_window} - T_{beacon} - T_{ATIM\_tr}), \end{aligned} \tag{12}$$

where E_{beacon} is the power consumed in receiving a beacon frame, and T_{ATIM_tr} is the duration for transmitting an ATIM frame which can be modeled as

$$T_{ATIM\_tr} = T_{ATIM} + T_{ACK} + SIFS. \tag{13}$$

The power consumption for delivering a data frame is

$$E_{data\_tx} = P_{tx} \times T_{data} + P_{rx} \times T_{ACK} + P_{idle} \times SIFS, \tag{14}$$

Table 3 System parameters

Parameter	Value	Parameter	Value
Bandwidth	54 Mbps	SIFS	16 μs
CW_{Min}	15	DIFS	34 μs
CW_{Max}	1023	Propagation delay	1 μs
Slot time	9 μs	Retry limit	4
Packet size	1000 bytes	PHY	192 μs
Network load	50 %	P_{tx}	1.346 w
P_{rx}	0.900 w	P_{idle}	0.741 w

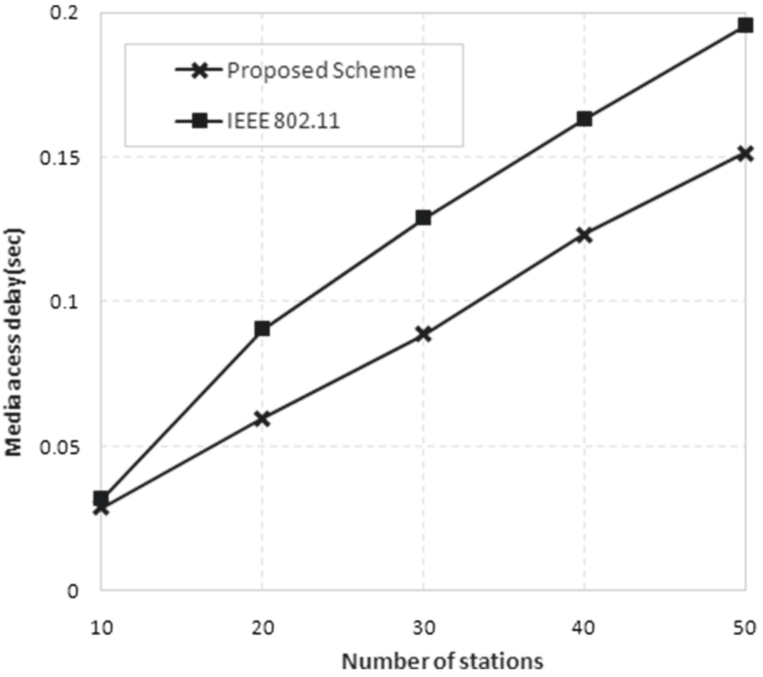

Fig. 9 Media access delay

and the power consumption for receiving a frame is

$$E_{data\_rx} = P_{rx} \times T_{data} + P_{tx} \times T_{ACK} + P_{idle} \times SIFS. \quad (15)$$

According to the legacy PSM, if a device delivers an ATIM successfully, it will stay active after the ATIM window. Thus, the power consumed in beyond ATIM window can be modeled as

$$E_{legacy\_beyondATIM} = P_{rx} \times T_{rx\_data} + P_{tx} \times T_{tx\_data} + P_{idle} \times (T_{beyond} - T_{rx\_data} - T_{tx\_data}). \quad (16)$$

Combining (12) and (16), we can get the power consumption of the tagged device in a BI based on legacy PSM

$$E_{legacy\_total} = E_{ATIM\_window} + E_{legacy\_beyondATIM}. \quad (17)$$

In the proposed scheme, the tagged device performs the same as legacy PSM in ATIM window. In the beyond ATIM window, the device continually senses the channel, and as soon as its BC decreases to 0, the device starts to transmit. When the device completes its transmission, it enters into doze mode. Assuming the tagged device has reserved a BC with *i*, we can get the power consumed in beyond ATIM window as

$$E_{proposed\_beyondATIM} = P_{rx} \times T_{rx\_data} + P_{tx} \times T_{tx\_data} + P_{idle} \times [i(DIFS + T_{slot}) + (i-1)T_s], \quad (18)$$

where T_s is the time spent in exchanging one data frame, which has been given in (2). The total power consumed for a device operated in proposed PSM is

$$E_{proposed\_total} = E_{ATIM\_window} + E_{proposed\_beyondATIM}. \quad (19)$$

Combining (12) with (19) we can give a comparison of power consumptions between legacy PSM and proposed schemes, using the parameters given by Table 3. It is found from Fig. 10 that our proposed scheme has

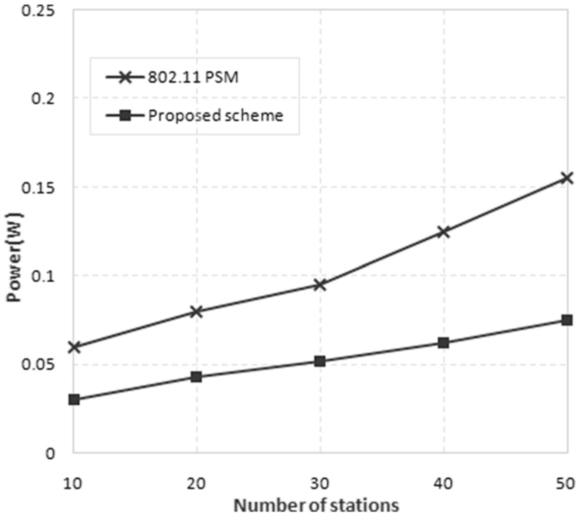

Fig. 10 Power consumption

significantly improved the average power consumption. This improvement is achieved by shortening the channel sensing period.

5 Simulation

We have conducted simulations using OPNET, and the results are presented in this section. In the first part of the simulations, we investigate how the network size affects the performance of the proposed scheme. The numbers of devices in an IBSS are changed from 10 to 50 with a step of 10, and in each scenario, half of the devices are PSM devices that have frames buffered for the other half. The destination device of each PSM device is fixed, and those destinations have no traffic to transmit. Devices transmit CBR (constant bit rate) traffic to destinations with a network load of 50 %. The duration of BI is 100 ms, the ATIM window is 20 ms, and the devices are deployed randomly without mobility. The details of the other parameters are given in Table 3.

Figure 11 shows the average media access delays of networks with different sizes. We find that the proposed scheme reduces the average delay very efficiently. It is because the reserved BCs in the proposed scheme have smaller values compared to the randomly chosen ones in legacy PSM. Moreover, there would be no collisions as no BCs are identical in our proposed scheme. On the other hand, it is found that in 802.11 PSM, the media access delay from simulation rises faster than that of analysis as the network size grows. We remind that the analytic model we built adopts the assumptions that no collision occurs and CW of each device keeps the minimum value. The results from simulation prove that when the network size increases, the collision occurs more frequently which degrades network performance.

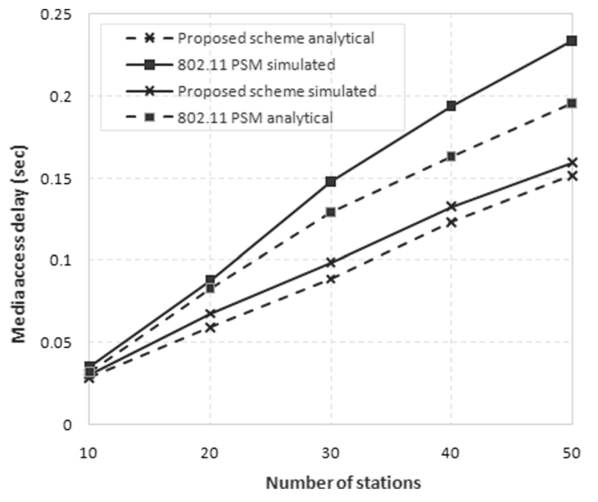

Fig. 11 Media access delay

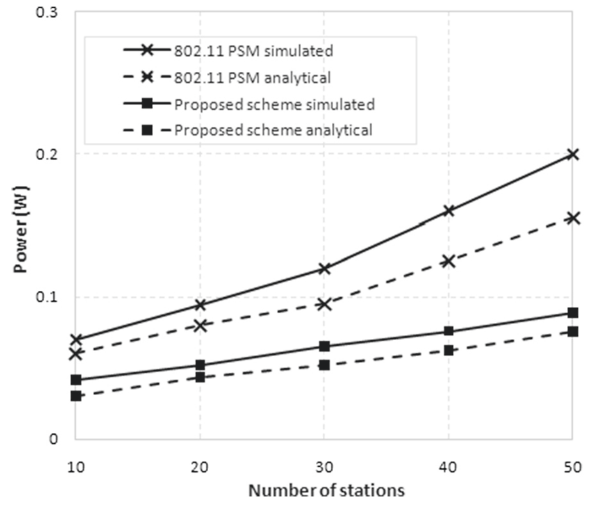

Fig. 12 Power consumption

Figure 12 shows the average power consumptions in both schemes; compared to the legacy PSM, our proposed scheme consumes much less power. It can be inferred that since the proposed scheme is reservation-based, the power consumed for collision and long period of idle channel is saved.

The next part of the simulation focuses on the effect of the network load to the performance of our proposed scheme. The configurations of the scenarios have referred to [16]. An IBSS with 30 devices is constructed, and half of the devices have traffic destined to the other half. Simulated network loads are 30, 40, 50, 60, and 70 %, measured as a fraction of the channel bit rate of 54 Mbps. The application used by the devices is the same as the previous simulation. Figure 13 shows that the average power

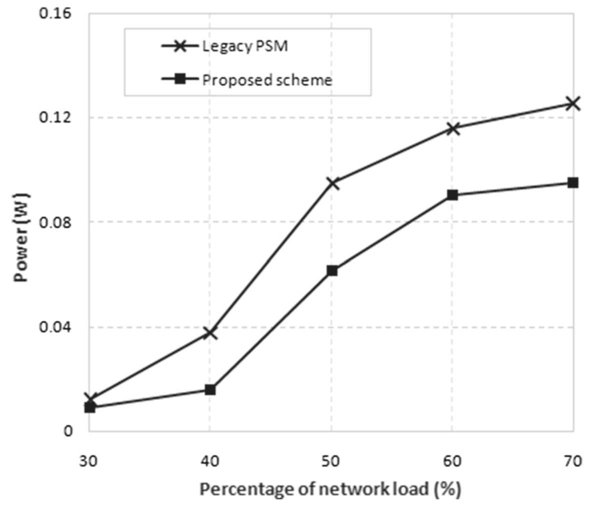

Fig. 13 Power consumption vs. network load

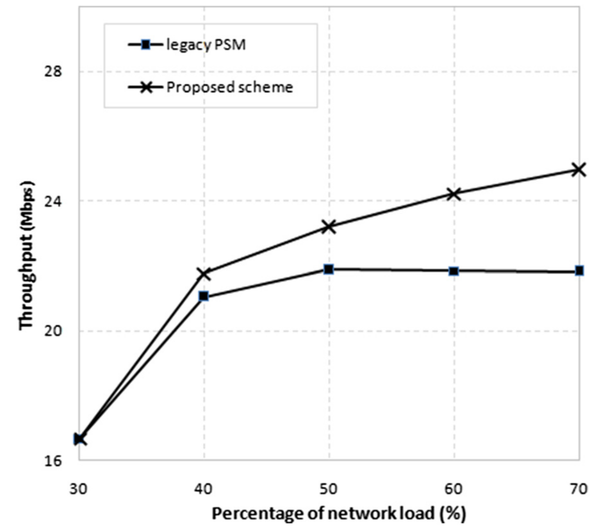

Fig. 14 Network throughput vs. network load

consumptions in both schemes increase as the network load grows, but that of our proposed scheme stays in a lower level.

Figure 14 depicts the overall network throughputs of both proposed and legacy schemes. One can find, after the network load reaches to 50 %, throughput of the legacy scheme starts to reduce slowly, while in our proposed scheme, it rises up as the network load increases. It is because, in the legacy PSM, when the network load increases, competitions among devices introduce more collisions. In our proposed scheme, however, devices access the channel using their reserved BCs, and the performance will not be affected much by the network load.

6 Conclusions

We have provided solutions to improve the performance of 802.11 PSM for IoT. A BC reservation scheme is proposed such that the devices transmit their data with lower collision probability by using their reserved BCs. Our proposal removes collisions resulted from the identically chosen BCs, and effectively reduces long periods of idle channels caused by large BCs. Also a neighbor polling method is adopted for mitigation of the hidden terminal problem: a wireless device affected by the hidden terminals can transmit an ATIM frame by the polling from a neighbor device, and thus reserves a BC. By building analytic models and performing simulations, we have shown that our proposed scheme effectively reduces power consumptions, while increasing network performance.

Competing interests

The authors declare that there are no competing interests regarding the publication of this paper.

Acknowledgments

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2013R1A1A2008855), in part by the research grant of Kwangwoon University in 2015 and the Startup Foundation of Yangzhou University (137010869).

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Received: 27 November 2015 Accepted: 12 January 2016

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