Named Data Networking Enabled Power Saving Mode Design for WLAN

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***Abstract*—The energy consumption of wireless interface is critical to power-constrained mobile devices. To improve energy efficiency for WLAN stations, power saving mode (PSM) is proposed, to manage the time spent in idle listening (IL) state. The hurdle is that the receiver has no knowledge about when the pending data will arrive under end-to-end communication protocols (TCP/IP), making each station spend enormous time in IL to wait for the pending data. To overcome this limitation, in this paper, we propose a named data networking (NDN) enabled PSM, namely, NDN-PSM, which leverages NDN communication architecture to cut down unnecessary IL time. In particular, we devise two new power states in *NDN-PSM*, i.e., light doze and deep doze, to precisely map to the underlying data arriving states. The inherent receiver-driven pattern of NDN can effectively drive the stations to the deep doze state for power saving, and to light doze state for timely data reception. Considering the IL time waste during channel contention, we further design a channel contention control mechanism in *NDN-PSM*, in which stations will switch to the light doze state if the channel is perceived to be busy. The power consumption model of the proposed NDN-PSM is theoretically analyzed and verified via numerical results. At last, we implement *NDN-PSM* in NS-3 by adopting the ndnSIM module and conduct extensive simulations to demonstrate the efficacy of *NDN-PSM*. Specifically, compared to the existing PSM mechanism, *NDN-PSM* reduces 56% power consumption by cutting down unnecessary IL time, and meanwhile enables low-delay transmission.**

***Index Terms*—Named data networking, power saving mode, WLAN, Idle listening time, pending interest table.**

I. INTRODUCTION

TO ENABLE various mobile applications, wireless connection (e.g., via WLAN) becomes essential. However, the enormous power consumption for power constrained mobile devices has become insurmountable for the system endurance [2]–[5]. For example, it is reported that wireless cards consume more than 10% of the total power consumption in current laptops [6]–[8], which paves a requisite direction towards power saving for wireless interfaces to extend the system endurance.

In IEEE 802.11 standards [9], power saving mode (PSM) is proposed to improve energy efficiency for mobile stations (STAs), in which there are two power states, i.e., doze state and awake state. In doze state, the station sleeps with the minimum power consumption, while in awake state the station stays either in idle listening (IL), receiving, or transmitting states. In PSM, when stations have no data to transmit, they normally switch to the doze state directly. However, for data reception, all stations have to wake up periodically to listen to the Beacon frame transmitted by the access point (AP), which contains the traffic indication map (TIM), listing out those stations who need to wake up to be prepared for the data reception. To this end, enormous time will be spent in IL state to wait for the pending frames. There are two major reasons making stations consume the dominant proportion of time in IL state. First, the medium access of IEEE 802.11 is based on CSMA, where each station has to stay in IL state to check the channel status, and access the channel if available. Second, for data dissemination, as each station has no knowledge about the future pending data, it has to stay in IL state conservatively to wait for unpredictably arriving packets. According to [10] and our experiment II-A, the power consumption of IL state is rather comparable to that of transmission and reception states, which further aggravates the energy inefficiency. In IEEE 802.11, the efficacy of PSM lies in the time management when the station is not transmitting or receiving data. If larger portion of this time is spent in the doze state rather than the IL state, the energy consumption will be significantly saved. Therefore, reducing the IL time is the ultimate approach to improve energy efficiency in WLAN.

In the literature, many solutions to improve energy efficiency in WLAN have been proposed [11]. Several enhanced PSMs are customized to fit different scenarios, such as Unscheduled Automatic Power Save Delivery (i.e., 11e), Power Save Multi-Poll (i.e., 11n/ac), Spatial Multiplexing Power Save (i.e., 11n), Target Wake Time (i.e., 11ax), etc. In the proposed schemes, solutions are based on TCP/IP protocols, which may fail to achieve the maximum energy saving gain since the pending packets cannot be well predicted. Other approaches are proposed

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Manuscript received March 19, 2019; revised June 13, 2019; accepted November 4, 2019. Date of publication November 11, 2019; date of current version January 15, 2020. This work was supported in part by the Hunan Provincial Natural Science Foundation of China under Grant 2017JJ2332, in part by the Fundamental Research Funds for the Central Universities of Central South University 2017zzts146, and in part by Natural Sciences and Engineering Research Council (NSERC) of Canada. This paper was presented in part at the IEEE International Conference on Communications, Shanghai, China, May 2019 [1]. The review of this article was coordinated by Prof. I. Bisio. *(Corresponding author: Wang Yang.)*

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Digital Object Identifier 10.1109/TVT.2019.2952665

to improve the performance of PSM, which can be classified into two categories, i.e., reducing the energy consumption in IL state and reducing the time in IL state. However, these PSMs apply to the end-to-end protocols, which may be inefficient in balancing the tradeoff between the power saving and data reception delay due to the uncertainty of pending data.

Named Data Networking (NDN) [12]–[14] is an innovative future network architecture, which transforms the network communication model from host-centric to data-centric. In wireless NDN [15], [16], each station maintains a Pending Interest Table (PIT) which records all incoming Interest packet information. By checking the PIT status information, the station is able to ”predict” whether there is requested data coming back from the Internet. Leveraging this intrinsic advantage of NDN, in this paper, we propose a new PSM named as *NDN-PSM*, to cut down unnecessary IL time for energy efficiency. In *NDN-PSM*, we devise two new power states, i.e., light doze and deep doze state, in order to precisely map to the underlying data arriving stage. Specifically, by checking the PIT status, each station can switch to the deep doze state (i.e., sleeping for a long duration) if there is no pending data coming back from the Internet (i.e, PIT=0). If there is pending data (i.e., PIT=1), the station enters the light doze state, in which instead of keeping waiting, the station sleeps for a short duration and wakes up periodically, to achieve both power saving and lower data reception delay. After receiving the TIM information, indicating that the AP has cached the requested data for the station, it will switch to the IL state preparing for the data reception. In addition, considering the extravagant power consumption at the channel contending stage, we integrate a channel contention control mechanism in our *NDN-PSM*, in which instead of keeping unsuccessful contending, the station will switch to the light doze state if the channel is perceived to be busy. In this way, not only the channel congestion are mitigated, stations also avoid the unnecessary energy consumption caused by collision and retransmission.

For performance analysis, we first establish a probabilistic model to characterize power consumption in IEEE 802.11 PSM and the proposed *NDN-PSM*, respectively. Then, numerical results are provided to demonstrate the advantages of the proposed scheme. At last, we implement our *NDN-PSM* in NS-3 by using *ndnSIM* tools and conduct extensive simulations to demonstrate its efficacy. Specifically, compared with the current PSM, *NDN-PSM* can reduce by up to 56% of power consumption through cutting down much unnecessary IL time. Meanwhile, by switching the power state among the light doze and deep doze state intelligently, the transmission delay is also guaranteed.

The main contributions are summarized as follows.

- We collect extensive WLAN traces and conduct statistical analysis on state durations. We reveal that the IL state takes the dominant percentage of WLAN time, which is the main cause of energy inefficiency.
- Based on NDN communication patterns, we propose a new PSM named as *NDN-PSM*, to cut down unnecessary IL time by predicting the pending data proactively, in which we devise new power states to map the underlying data arriving states and integrate a channel contention control mechanism to prevent inefficient channel contentions in WLAN.
- We establish the probability-based power consumption model and provide theoretical performance analysis of the proposed *NDN-PSM*.
- We implement *NDN-PSM* in NS-3 and conduct extensive simulations to demonstrate its efficiency; the result shows that our power saving mode can reduce the average power consumption by up to 56%.

The remainder of this paper is organized as follows. In Section II, we present the problem statement. We elaborate our *NDN-PSM* design in Section III. Section IV gives the *NDN-PSM* operation process. Theoretical performance analysis and simulation results are carried out in Section V and VI, respectively. We review the related work in Section VII, and conclude this paper in Section VIII.

II. PROBLEM STATEMENT

In this section, we first present some experiment studies to disclose the limitation of current PSM, and then provide the problem statement.

A. IL State Prevalence During WLAN Connection

To understand how power states work in realistic WLAN, we recruit volunteers to help us collect packet-level WLAN traces. Assume multiple stations are requesting contents for different applications, such as online game, video live streaming, news or non-real-time social applications (e.g., WeChat, Weibo). Specifically, STA1 and STA2 are browsing news and chatting online, STA3 and STA4 are watching live video streaming, and STA5 and STA6 are playing online games. During the experiments, other Internet services are turned off, and we use Wireshark to capture all sending/receiving packets. We analyze the IEEE 802.11 protocol flags to label out the duration of each power state. Particularly, as shown in Fig. 1, given a WLAN connection session, the “PS-Poll” flag indicates the beginning of the packet receiving (RX) stage. The flag “More data=1” in each data packet keeps the RX stage until the flag “More data=0” appears in the packet. If the station transmits packets to AP, then it enters the transmitting (TX) stage. In addition, the station will enter the Sleep state after sending out a null data frame (with flag PWR=1) to AP, and can wake up at any time if there is a packet to be transmitted. Besides the RX, TX, and Sleep states, the remaining time is counted as the IL state time. After extracting the state time for all connection sessions, we plot all state time ratios of different STAs, as shown in Fig. 2. It can be seen that as the STA becomes more active, the time ratio of TX/RX states increases accordingly. Nevertheless, IL state still takes up the dominant percentage in all STAs. For instance, when the station intermittently requesting data (e.g., STA1 and STA2), it will spend more than 80% of time in IL state; even for the STAs that transmit continuously (e.g., STA5 and STA6), the IL state ratio reaches up to 44%. Therefore, *IL state accounts for the dominant WLAN time no matter what the underlying application data is requesting*. Besides, by analyzing

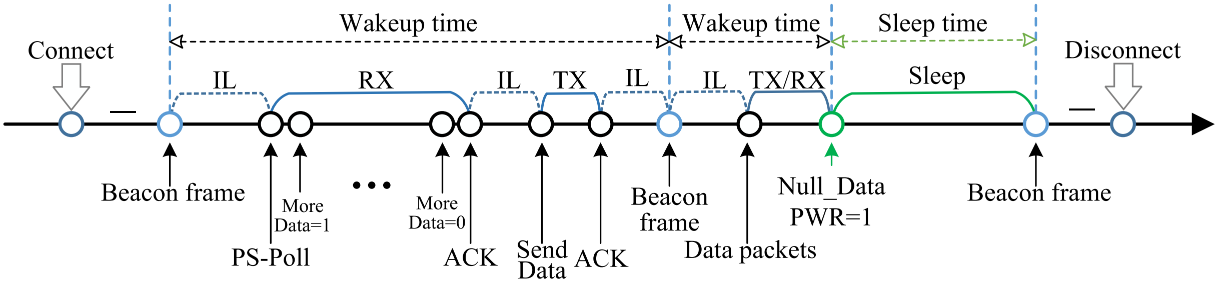

Fig. 1. The process of labeling power state time duration in WLAN.

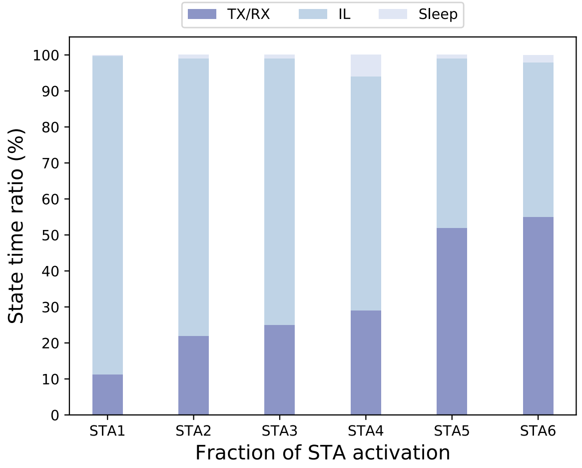

Fig. 2. Power state time ratio (RX/TX, IL, Sleep).

TABLE I
POWER CONSUMPTION OF MOBILE DEVICES

Modes	Power consumption (mW)			
	Wavelan [10]	Dell [17]	E-mili [10]	Intel [18]
Sleep	177	99	10.8	220
IL	1319	660	219.6	1270
RX	1452	759	223.2	1340
TX	1675	1089	127	1440

the public data set in SIGCOMM'08,[1] it was also verified that the station spends over 87.2% time in IL state even when PSM is enabled [10], which cross verifies our conclusion.

Considerable Power Consumption of IL State. Given the fact that IL is the dominant state that consumes most of the time, we study about the energy consumption of IL state, which determines the energy efficiency in WLAN. Table I lists the energy consumption of Sleep, IL, RX, and TX states in Wi-Fi cards from different manufacturers. Although energy consumption differs in different Wi-Fi cards due to their distinct technique methodologies, it can be seen that the energy consumption of IL state is rather comparable to that of RX and TX states, and is significantly higher than that of Sleep state.

The above extensive analysis reveals that stations normally spend mostly of time in IL state and cannot go to Sleep state efficiently even when the PSM is enabled in WLAN, while the energy consumption in IL state is rather considerable, resulting in energy inefficiency. Essentially, it is mainly because the current end-to-end communication protocol fails to predict when the requested data will arrive, which significantly increases the IL state duration. Hence, reducing the IL time could effectively reduce power consumption of stations in WLAN.

B. Problem Statement

As mentioned in the previous subsection, we consider a typical WLAN scenario where there is an AP providing multiple stations with Internet access services. The main objective of mobile stations is to minimize the idle listening time and energy consumption to achieve a longer running time in WLAN. We have the following purpose in this paper.

(i) **Idle Listening Time.** There are two underlying conditions, which could make a station enter the IL state. First, if there are packets to be sent, the station will switch to IL state for channel listening, in order to access the transmission medium. Second, if the station has pending packets from the AP, it will keep in IL state to wait for the data arriving. As the station is unable to know when the AP has fetched its downlink data and prepared for the delivery, it will spend enormous time in IL state especially when the number of stations is large, which is the main focuses of this work.

(ii) **Energy Consumption.** The goal is to save the energy consumption for stations. Specifically, within a long-term duration H, we formulate our energy saving problem as follows:

$$\begin{aligned} \min_{\{T_{il}^h(i)\}} \quad & \frac{1}{H}\sum_{h=1}^{H}\sum_{i=1}^{n} E_i^h, \\ \text{s. t.} \quad & T_{sl}^h(i) + T_{rx}^h(i) + T_{tx}^h(i) + T_{il}^h(i) = S, \end{aligned} \tag{1}$$

where

$$\begin{aligned} E_i^h &= W_{sl}T_{sl}^h(i) + W_{rx}T_{rx}^h(i) + W_{tx}T_{tx}^h(i) \\ &\quad + W_{il}T_{il}^h(i), \end{aligned} \tag{2}$$

n is the number of stations in the WLAN, W_{sl}, W_{rx}, W_{tx}, and W_{il} are fixed powers of Sleep, RX, TX, and IL states, respectively. For the station i and the time slot S,

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[1] Note that, as the current public data set is a little out-of-date while the WLAN technique evolves rapidly, in this paper, we derive our conclusions mainly based on our newly collected wireless data trace.

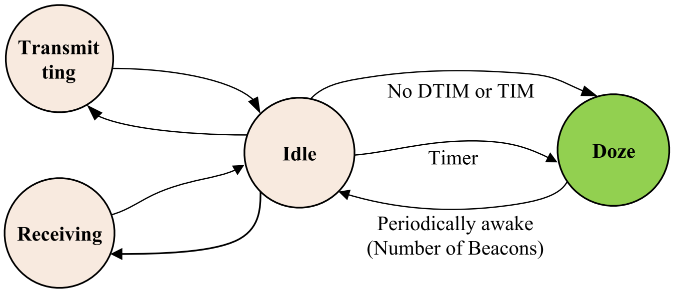

Fig. 3. Power states switching in current PSM.

$T_{sl}^h(i)$, $T_{rx}^h(i)$, $T_{tx}^h(i)$, and $T_{il}^h(i)$ are durations in Sleep, RX, TX, and IL states, respectively.

When the station is always in IL state, although the power consumption is significant, the transmission delay (including the data transmission and reception process) can be well guaranteed. In this paper, we also consider the balance between the energy saving and transmission delay. To summarize, by reducing the IL time, the goal of the proposed scheme is to minimize the total energy consumption in the long run without increasing the transmission delay.

III. DESIGN OF *NDN-PSM*

In this section, we first present necessary preliminaries about PSM and NDN architecture. Then, elaborate the *NDN-PSM* design. Specifically, as each NDN node is able to know whether there is pending data for itself, we first devise fine-grained power states in accordance to the underlying data arriving states, and detail the power state switch scheme in order to reduce as much IL time as possible. We then investigate the parameter setting to balance the tradeoff between the power saving and transmission delay. Considering the exceedingly high power consumption on channel contending when the channel is busy, we further integrate a channel contention control mechanism in *NDN-PSM* to avoid unnecessary channel contention.

A. Preliminaries About PSM and NDN

1) Power Saving Mode (PSM): In current PSM, stations have four power states according to the underlying data transmission requirements: Doze (Sleep), Idle, TX, and RX state as shown in Fig. 3. The Doze state consumes the least energy, and the station is in deep sleep and cannot listen to the channel or transmit/receive data. As specified by IEEE 802.11 PSM, the station will inform the AP and then switch to the Doze state when there is no data transmission within a duration (typically 200 ms [19]).

TIM is an important element in IEEE 802.11 PSM, which can wake up stations when their unicast frames have been buffered at the AP. The delivery traffic indication message (DTIM) is a special version of the TIM which indicates that broadcast or multicast frames of stations have been buffered at the AP. The AP should buffer all data destined to the station when the station is in the doze state. For the station in doze state, it would periodically wake up and switch to the IL state, in order to receive the TIM frame and check whether there is data buffered for itself. If the TIM indicates there is data pending for the station, it will send out a PS-Poll frame to respond to the AP, otherwise the station will go back to the doze state. After the station sending out the PS-Poll frame, it will begin to contend the channel for data reception. When the station has received all buffered data from the AP, it will go back to the doze state again.

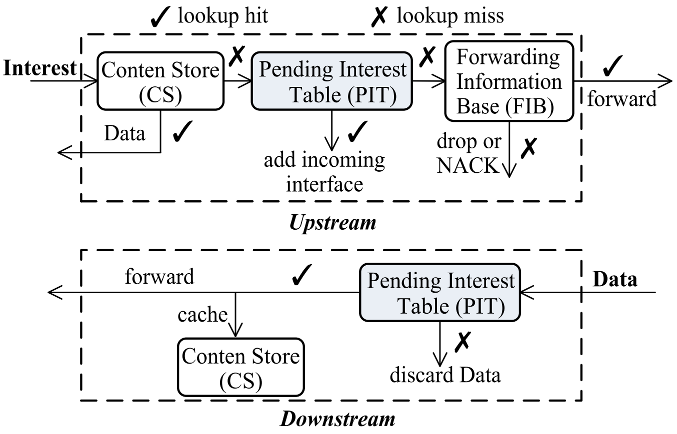

Fig. 4. NDN node forwarding process.

2) NDN Architecture: NDN [20]–[22] is a promising architecture for the next-generation network, especially for wireless network [23]–[25], which is able to handle consumer mobility and support multicast applications without additional protocols [20]. In current end-to-end (TCP/IP) architecture, stations keep awake to receive data that may not belong to itself, which wastes significant energy. In contrast, NDN is a receiver-driven communication architecture. If the station does not send *Interest* packet, it means that there is no data from the network pending for the station. Thus, it is unnecessary to keep listening to the channel, and even to wake up from the Sleep state. In addition, NDN nodes can periodically check their own PIT status to figure out whether the requested data is returned. Thus, there is unnecessary to wait for the requested data in IL state, which also significantly cuts down the IL time. Therefore, it is very beneficial to design a power saving scheme under the NDN architecture.

Specifically, there are two types of packets, i.e., *Interest* and *Data* packet in the NDN architecture. Each NDN node maintains three tables: 1) Content Store (CS), 2) Pending Interest Table (PIT), and 3) Forward Information Base (FIB) [12], where CS temporarily stores the packets returned to the NDN node, PIT table records all the incoming *Interest* packets that the node has forwarded to the FIB but have not yet been satisfied, and the FIB is used to forward *Interest* packet to the next potential hop which has stored the matched data. The detailed NDN forwarding process is shown in Fig. 4. Particularly, in the Upstream procedure, the NDN node generates or receives an *Interest* packet to request for certain data packets. It will first check its own CS, and return the data if the CS has stored the data, otherwise it transmits the request to the PIT table. The NDN node will add an entry to PIT and then forward to FIB if the requested data appears for the first time in the PIT table. For multiple *Interest* packets which request for the same data packets, the node will aggregate the PIT entry and forward only one *Interest* packet to the next hop.

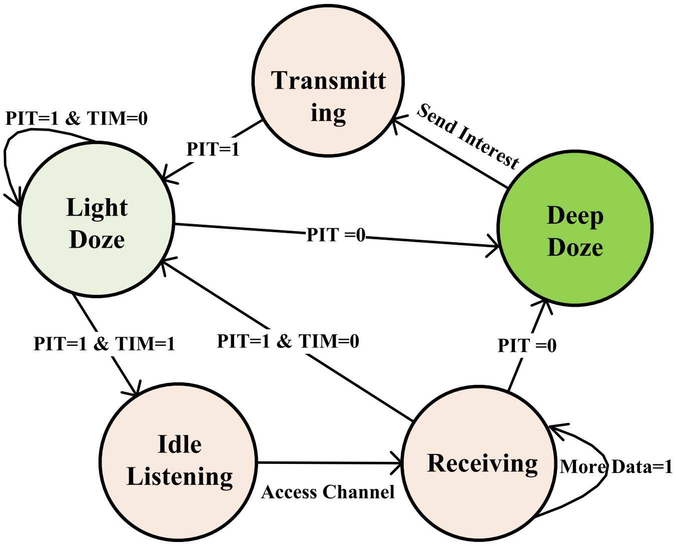

Fig. 5. Power states and switch process in *NDN-PSM*.

In the Downstream procedure, when the NDN node receives a *Data* packet, it will first match its PIT and forward the data to the next hop if there is the corresponding entry in the PIT table, otherwise, the node will drop the data. The requested data packets go back to the consumer following the reverse path that the *Interest* packet has been forwarded.

B. Power States in NDN-PSM

In accordance to the underlying data arriving states, in *NDN-PSM*, we design the following five power states:

Deep doze (Sleep). When there is no PIT entry or the PIT entry has timed out, i.e., PIT=0, it means there is no data pending for the station and the station switches to the deep doze state immediately. In deep doze state, the station sleeps for a long duration and saves the most power consumption.

TX/RX. The station is transmitting or receiving packets.

Light Doze. When the station switches to the light doze state, the station will periodically wake up to listen the Beacon frame for the TIM information. In this power state, it means that the station has the pending data (i.e., PIT=1), while the data has not arrived and the station is waiting for it (i.e., TIM=0) in light doze state.

Idle listening (IL). When the station switches to the Idle state, the station will continue to listening to the channel for medium access and prepare for data reception, which means that its requested data has been cached at the AP, i.e., PIT=1 and TIM=1.

Specifically, the power states and the switch process are shown in Fig. 5. Generally, when PIT=0, it means there is no interested data related to the station or the interested data is timeout. Thus, the station goes to the deep doze state immediately. There are two conditions, which can make the station awake from deep doze state. First, if the station needs to transmit data, it will wake up immediately and switch to the TX state directly. Second, the station would wake up periodically after an interval to synchronize its time and act as a heartbeat in response to the AP, and go back to the deep doze state again. NDN is a receiver-driven communication architecture, which indicating that the station can switch to other power states only after it requests for the data first, i.e., transmitting data. After requesting for data, the PIT becomes not NULL (i.e., PIT=1), and it means that there is an incoming entry of an *Interest* packet and the *data* packets will come back in the reverse path in the matched PIT entry. Thus, the power state switches from the TX state to the light doze state. In the light doze state, the station wakes up in every Beacon frame to check the TIM information. By doing so, instead of keeping waiting for the pending data, under the light doze state, the station can save much power by waking up periodically. If TIM=1, which means that the AP has buffered all the data for the station, the station will switch from the light doze state to the IL state, to compete for the channel and prepare for the data reception. After the station occupies the channel, it will go to the RX state for data reception, and the flag "More data=1" in each packet means that there is more data waiting for reception and the station should continue stay in RX state. When TIM=0 and meanwhile PIT=1, the station will switch to the light doze state to wait for the requested data until all data comes back from AP. The station will remove the corresponding PIT entry and switch to deep doze state if the PIT entry timeout or the PIT entry has satisfied. In light doze, IL, and RX states, PIT=0 means there is no pending data for the station, the station would go to the deep doze state immediately.

If the station spends more time in deep doze state and light doze state, the power consumption can be significantly reduced. In order to reduce the IL time in *NDN-PSM*, we use the PIT and TIM status to cut down unnecessary IL time. Particularly, if the PIT is Null, there is no need for the station to wait for the return data and the station goes to the deep doze state. If PIT=0 and TIM=0, the requested data has not been returned and the station goes to the light doze state for power saving. The station wakes up depending on the time interval setting, which is set to be T_{LI}^{L} and T_{LI}^{D} in light doze state and deep doze state, respectively. In summary, the NDN-PSM scheme has a finer-grained mechanism to make the STA stay in the two doze states as long as possible.

C. Balancing Power Saving and Transmission Delay

Generally, we can enlarge the parameters T_{LI}^{L} and T_{LI}^{D} to save the energy consumption. However, the data delay is also of significance for wireless communication, which inevitably contradicts with the power saving. Specifically, if we enlarge T_{LI}^{L}, we cannot perceive the TIM status at the earliest stage. For example, if the Beacon indicating TIM=1 comes during the sleeping period T_{LI}^{L}, the station would fail to receive the packets and can obtain the information through the first Beacon after it wakes up, which prolongs the medium access and data delays. In contrast, if we set T_{LI}^{L}, the station keeps waiting for the pending data (i.e., in IL state), and can response to the data arriving immediately, while the energy consumption is unacceptable. Compared with the current PSM scheme, the light doze state of *NDN-PSM* is able to reduce the IL time by slightly sacrificing the transmission delay performance. On the other hand, T_{LI}^{D} can be increase at the following cost. First, in the deep doze, if the station sleeps for a long duration, it cannot hear Beacon frames on time, resulting in time drift compared with the time reference

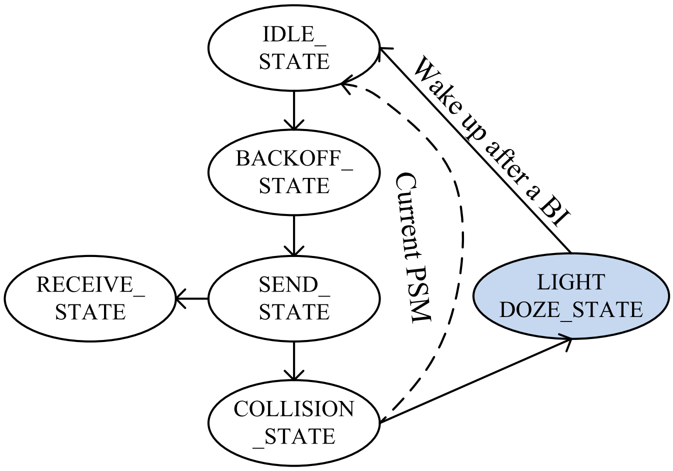

Fig. 6. Channel contention management.

from the AP; as a result, the station may miss Beacon frames after sleeping. Second, during the long sleeping period T_{LI}^{D}, the station will miss all controlling Beacons from the AP and cannot response to it timely, which may be dissociated by the AP.

D. Channel Contention Management

When the station wakes up, it will go to the IL state to listen to the channel and contend for the channel medium. However, when the number of contending stations increases, the probability of collision will also grow. As shown in Fig. 6, when the station wakes up, it randomly selects a back-off counter and waits for the channel at the IL state. After the back-off counter reaches to 0, the station begins to transmit data packets and set the channel is busy. If the station successfully accesses the channel and receives all the requested data, the channel will be released to be free. However, if there are multiple stations contend the channel simultaneously, the station may meet channel collisions and fail to access the channel. In current PSM, the station will go back to the back-off procedure and contend for the channel again. If the number of contending stations is large, frequent collisions will happen and stations will have to spent long time in IL state, resulting in significant power consumption. In *NDN-PSM*, we limit the maximum back-off procedures. When the number of back-off procedures exceeds the threshold, the station will go to the light doze state and wake up for contention after a Beacon Interval (BI).

IV. *NDN-PSM* OPERATION PROCESS

Figure 7 illustrates the work flow of proposed *NDN-PSM*. Specifically, STA1 and STA2 are adopting the basic IEEE 802.11 PSM mechanism while STA3 and STA4 are using the proposed *NDN-PSM* mechanism. We assume that the listening interval (LI) of STA1, STA2, STA3, and SAT4 are set to be one BI, two BIs, two BIs, and four BIs, respectively.

Relying on the PIT status, the proposed *NDN-PSM* scheme is able to proactively predict whether there is pending data, through which *NDN-PSM* can reduce the IL duration and meanwhile improves the light and deep doze state durations. Compared with TCP/IP architecture, *NDN-PSM* can reduce the IL time in the three aspects: 1) *Waiting for the pending data*, 2) *Channel contention*, and 3) *Without receiving the TIM information*.

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1) Waiting for the Pending Data: STA2 and STA3 send the request packet to the AP in the second Beacon frame. STA2 switches to the IL state waiting for the pending data after the requested packet is successfully sent to the AP. In contrast, STA3 goes into the light doze state waiting for the pending data. The reason is that the current PSM scheme cannot predict when time the pending data arrive by using the end-to-end communication protocol. *NDN-PSM* can use the PIT status information to make the station switches to the light doze state for power saving. When AP has cached all data for STA1, STA2, and STA3. STA1, STA2, and STA3 are waiting for data reception at the sixth Beacon frame. STA1 and STA2 are switched to the IL state for data reception in current PSM. However, STA3 is switched to light doze state waiting for the pending data in NDN-PSM. This is the basic idea that *NDN-PSM* can significantly reduce the power consumption compared with current PSM.

2) Channel Contention: At the third Beacon frame, STA1, STA2, and STA3 will contend for the channel simultaneously. As the STA1 gets the channel successfully, STA2 will stay in IL state to continue contending for the channel while STA3 can switch to the light doze state according to the channel contention management scheme in *NDN-PSM*. At the fourth Beacon frame, STA3 wakes up and contends for the channel with STA2. Once STA3 successfully accesses the channel, it sends the PS-Poll frame to retrieve the buffered data from the AP while STA2 still has to be in IL state waiting for the channel.

3) Without Receiving the TIM Information: In PSM, if the TIM loss or not received, the stations cannot determine whether there is traffic information from the AP through its own status information. However, *NDN-PSM* can use the PIT status information to determine whether to enter the doze state without TIM information. For example, all stations wake up to check the TIM information at the first Beacon frame. STA1 sends the PS-Poll frame to retrieve buffered data from the AP until *more data*=0 as its TIM equals 1. For STA2, STA3, and STA4, as they just wake up and miss the TIM information, STA2 has to go to the IL state while the STA3 and STA4 can switch to the deep doze state since PIT=0.

At the fifth Beacon frame, STA4 wakes up and goes into the light doze state as PIT is perceived to be 1, while STA3 switches to the deep doze state as it has finished the data reception and the entry of matching interface in PIT has been removed. STA2 still continues contending for the channel with STA1 and goes to the IL state again as STA1 occupies the channel.

In summary, given the same level of traffic arriving condition, there are more Sleep states at STA3 and STA4 than that of in STA1 and STA2. In addition, the proposed mechanism does not require significant changes in the IEEE 802.11 standards.

V. POWER CONSUMPTION ANALYTICAL MODELING

In this section, we establish the probabilistic power consumption model to analyze the performance of *NDN-PSM* theoretically. Specifically, we first devise the probability-based framework to model the transmission process of stations, based on

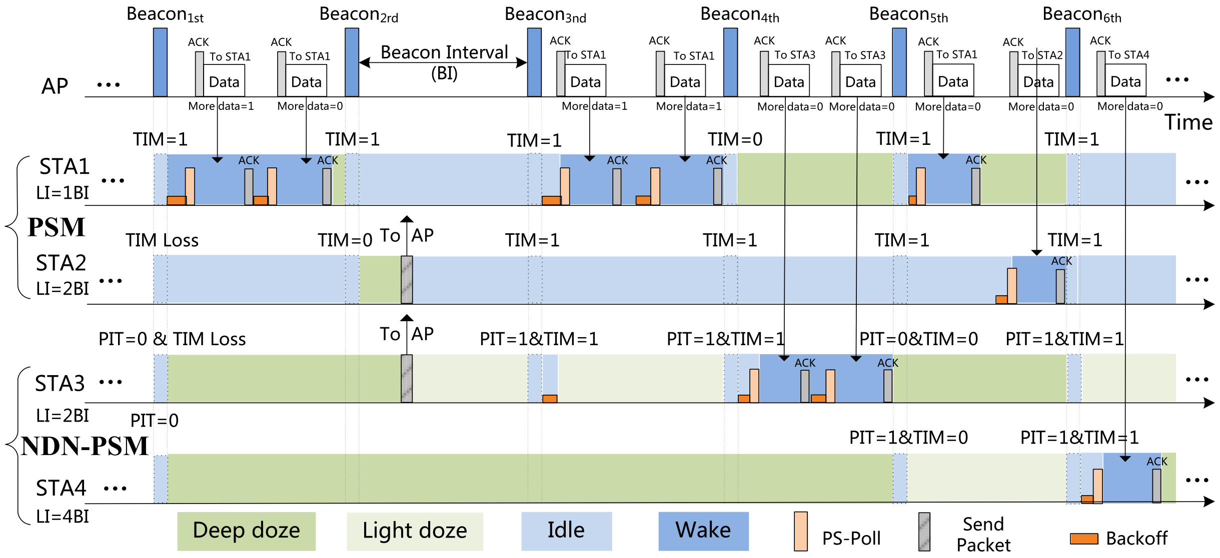


Fig. 7. The work flows of *NDN-PSM* and PSM in WLAN.

which we then drive the power consumption of IEEE 802.11 PSM and *NDN-PSM*, respectively. After that, we carry out numerical results to compare and analyze the power consumption performance.

To derive the analysis model of power consumption, we use the two-dimensional Markov chain model for the backoff process. This process is similar to the Bianchi's model [26] and its variants [17], [27]. We first calculate the probability of different states. Let n and m be the total number of stations and the number of stations in awake state (including RX, TX, and IL states), respectively. To make the analysis tractable, we assume that transmission behaviors of all stations are *independent and identically distributed*. Each station transmits a packet with a probability ε. Denote p_{tr} by the probability that there is at least one transmission among m contending stations, which can be calculated by [17], [26], $p_{tr} = 1-(1-\varepsilon)^m$. Similarly, let p_{col} be the probability of encountering a transmission collision, i.e., more than two stations transmit simultaneously, and p_{col} can be calculated as $p_{col} = 1-(1-\varepsilon)^{m-1}$.

The successful transmission happens only when exactly one station transmits on the channel and the other $(m-1)$ stations delay their transmission [17]. Thus, the successful transmission probability p_{suc} is

$$p_{suc} = \frac{m\varepsilon(1-\varepsilon)^{(m-1)}}{p_{tr}} = \frac{m\varepsilon(1-\varepsilon)^{(m-1)}}{1-(1-\varepsilon)^m}. \tag{3}$$

To compute the average time length of each transmission process, we consider three cases: 1) the probability is $1-p_{tr}$ when the transmission process is empty; 2) the probability is $p_{tr}p_{suc}$ when a successful transmission happens; and 3) the probability is $p_{tr}(1-p_{suc})$ when a transmission collision happens. Hence, the average time length L is given by

$$L = (1-p_{tr})\sigma + p_{tr}p_{suc}T_s + p_{tr}(1-p_{suc})T_c, \tag{4}$$

where σ, T_s, and T_c means the duration of an idle process, a successful transmission process, and a collision process, respectively.

In IEEE 802.11 standard, the duration of successful transmission and collision process can be given by [26]

$$\begin{cases} T_s = T_{poll} + T_{data} + T_{ack} + 2\cdot T_{SIFS} \\ T_c = T_{poll} + T_{DIFS} \end{cases}, \tag{5}$$

where T_{poll}, T_{data}, and T_{ack} means the duration of the PS-Poll, DATA, and ACK frames during the transmission, respectively.

A. *Power Consumption Analysis of* NDN-PSM

Based on the above probability basics during transmission process, we then derive the total average energy consumption of n stations in the NDN-PSM.

Specifically, we define E_{idle}, E_{suc}, E_{col}, E_{slp}, and E_{lit} as the average energy consumption during the process of idle listening, successful transmission, collision, sleep, and light doze, respectively.

(a) E_{idle}. The probability of the idle process p_{idle}, can be represented as

$$p_{idle} = (1-p_{tr}) = (1-\varepsilon)^m. \tag{6}$$

Then, the energy consumption can be computed as

$$E_{idle} = m\cdot\sigma\cdot p_{idle}\cdot W_{il}, \tag{7}$$

where W_{il} is the power of idle state.

(b) E_{suc}. The probability of the successful transmission process p_{succ}, is

$$p_{suc} = p_{tr}p_{suc} = m\varepsilon(1-\varepsilon)^{m-1}. \tag{8}$$

If there is a successful transmission process, $(m-1)$ stations should stay in the idle state. The station consumes the transmission power W_{tx} in the transmission state during the PS-Poll and ACK frames, and consumes the reception power W_{rx} in the receiving state during the data frame. Hence, E_{suc} can be represented as

$$E_{suc} = (m-1)T_s p_{suc} W_{il} + (T_{poll}+T_{ack})p_{suc}W_{tx} + T_{data}p_{suc}W_{rx}. \tag{9}$$

(c) E_{col}. The probability of the collision process p_{coll} is

$$p_{col} = p_{tr}(1 - p_{suc}). \tag{10}$$

When multiple stations access the channel simultaneously, these stations will collide with each other. During the collision period, stations consume the transmission power to transmit the PS-Poll frames. In contrast, the rest of the stations consume the idle power in the awake state. Therefore, E_{col} can be calculated as

$$E_{coll} = N_{col} T_c p_{col} W_{tx} + (m - N_{col}) T_c p_{col} W_{il}, \tag{11}$$

where N_{col} denotes the average number of colliding stations, i,e., accessing the channel together, and can be derived by [17],

$$N_{col} = \frac{\sum_{i=2}^{m} C_m^i \varepsilon^i (1-\varepsilon)^{(m-i)}}{p_{tr}(1 - p_{suc})}. \tag{12}$$

(d) E_{slp}. The effective sleep time is denoted by T_{slp}. As there are $(n - m)$ stations in the Sleep state, given the Sleep state power of W_{sl}, the energy consumption E_{slp} can be computed as

$$E_{slp} = (n - m) T_{slp} W_{sl}. \tag{13}$$

(e) E_{lit}. In *NDN-PSM*, if a station goes to the light doze state, it means that it will wait for each Beacon frame to check whether the data has been returned. In other words, the station has sent the requested Interest successfully but does not receive the returned data. Thus, the probability of the light doze state p_{lit} is

$$p_{lit} = p_{tr} p_{suc}. \tag{14}$$

Given the light doze power W_{lit} and the awake time in light doze T_{lit}, the power consumption E_{lit} can be represented by

$$E_{lit} = e \cdot T_{lit} \cdot p_{lit} \cdot W_{lit}, \tag{15}$$

where e is the average times of BI during the light doze state.

Finally, the total energy consumption of *NDN-PSM* is

$$E_{total}^{NDN-PSM} = E_{idle} + E_{suc} + E_{col} + E_{slp} + E_{lit}. \tag{16}$$

Compared with the IEEE 802.11 PSM scheme, Eq. (16) has an additional power consumption of light doze (E_{lit}). However, compared with the current PSM, the proposed NDN-PSM can significantly reduce the idle time in IL state and spend more time on doze state. Moreover, the power consumption of light doze is closed to deep doze state. Therefore, the NDN-PSM scheme can significantly reduce the total power consumption.

B. Numerical Results

In this section, we numerically calculate the power consumption and validate the analysis model, and give the comparing results between the analysis results and simulation results by using MATLAB. In *NDN-PSM*, each consumer decides whether to stay in awake state or switch to doze state after receiving the TIM information in Beacon frame from the AP. We set the default parameters from IEEE 802.11a protocols and the values of the power consumption in Table II. We consider a WLAN scenario where all stations are associated to the AP. The probability ε and p_{col} can be calculated by [17], [27],

TABLE II
SIMULATION PARAMETERS

Parameter	**Value**	**Parameter**	**Value**
Packet payload	1200 bytes	CS size	10000 packets
T_{PHY}	20 μs	T_{poll}	30 μs
T_{DIFS}	34 μs	T_{data}	143 μs
T_{ack}	27 μs	T_{slp}/T_{lit}	3/1 BI
T_{SIFS}	16 μs	Slot time (σ)	9 μs
W_{il}	1.27 W	Contention limit	4
W_{rx}	1.34 W	W_{tx}	1.44 W
W_{sl}/W_{lit}	0.11/0.22 W	Data rate	6-54 Mbps
CW_{min}/CW_{max}	16/1024	T_{BI}	100 ms

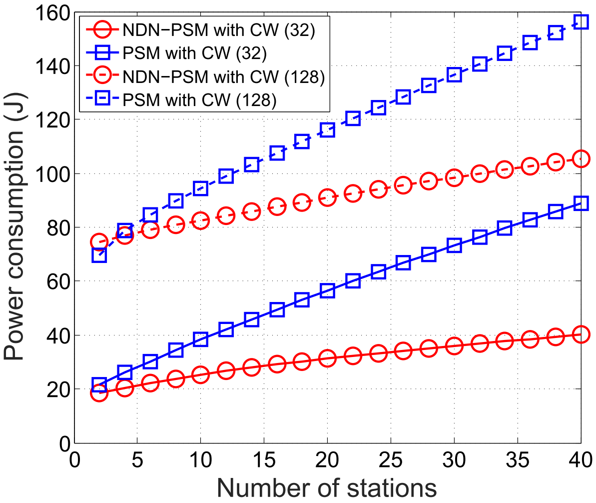


Fig. 8. Numerical results of power consumption.

$$\begin{cases} p_{col} = 1 - (1 - \varepsilon)^{m-1} \\ \varepsilon = \dfrac{2}{1 + CW_{min} + p_{coll} \sum_{k=0}^{w-1} (2p_{col})^k}, \end{cases} \tag{17}$$

where CW_{min} is the minimum size of the contention window, and w is maximum contention stage.

Figure 8 shows the analysis results of NDN-PSM and PSM in power consumption. It can be seen that the proposed *NDN-PSM* scheme is rather effective to reduce the power consumption when compared with the PSM scheme. In the both two PSMs, the power consumption increases as the number of stations increases. Moreover, as the size of CW decreases, the both two PSMs can reduce the power consumption. This is because reducing the CW approaches can reduce the waiting time and increases the probability of collision. In addition, as the number of stations increases, the gain of *NDN-PSM* over PSM also increase.

We also validate the analytical model by comparing the numerical results with the simulation results under the same parameter settings, where the simulation setup can be found in the following section. Fig. 9 shows the analytical and simulation result for *NDN-PSM* power consumption under different number of stations. As the number of stations increases from 5 to 40, the total power consumption grows in both two curves. Moreover, it

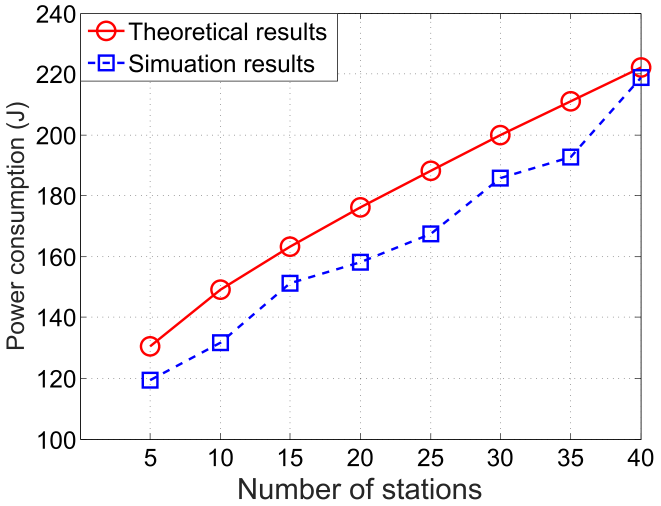


Fig. 9. Theoretical analysis and simulation results.

can be seen that there is no significant deviation between analysis and simulation results for power consumption, which validates the accuracy of the analytical model.

VI. PERFORMANCE EVALUATION

A. *Implementation and Simulation Setup*

We implement our *NDN-PSM* in NS-3 by adopting the ndnSIM module [28], which implements the NDN and information-centric networking communication model. Even though the current NS-3 version gives the interfaces for PSM, while it has not enabled the PSM functions. To enable the PSM functions, we modify the frame formats of Beacon, PS-Poll, NULL Data, and Association Response. In Beacon frame, we include the TIM tag to notify stations whether their pending data has been buffered at the AP. We supplement the PS-Poll frame, which is utilized by stations to request for the buffered data. In addition, the NULL Data frame is supplemented to notify the AP that the station would go to the Sleep state. To label each association, we include an association identifier in each Association Response frame, through which the AP can distinguish each station and notify them about the buffered data through the TIM tag. After modifications, we first implement PSM in NS-3 according to the IEEE 802.11 standards, based on which we then implement our *NDN-PSM* by adopting NDN communication models in ndnSIM module. In *NDN-PSM*, the light doze and deep doze states are implemented and stations can check the PIT status to predict the pending data proactively.

We consider the downlink scenario, where all stations associates to the same AP and have the same transmission rate, to evaluate the efficiency of PSMs. The network topology consists of a producer, a router, an AP, and various stations, in which both the producer-router and router-AP links are connected via the Point-To-Point (P2P) communication module. In addition, each station adopts the *ConsumerBatches* traffic generation model [28] to transmit *Interest* packets to the producer. Specifically, each station requests for 10 packets every second, i.e., transmitting a request every 100 ms and waiting for the packet back. We limit the maximum number of channel contention stage to be 4 in *NDN-PSM*. Detailed simulation parameters are listed in Table II.

Performance Metrics: We consider the following four metrics to evaluate the performance of *NDN-PSM*.

- **Idle Listening Time Ratio:** refers to the average percentage of time spent in IL state.
- **Total Power Consumption:** refers to the sum of all states energy consumption of a station.
- **Transmission Delay:** refers to the interval of time elapsed between the request packet transmitted and the requested packet received.
- **Packet Loss Rate:** refers to the number of packet losses to the total number of transmitted request packets.

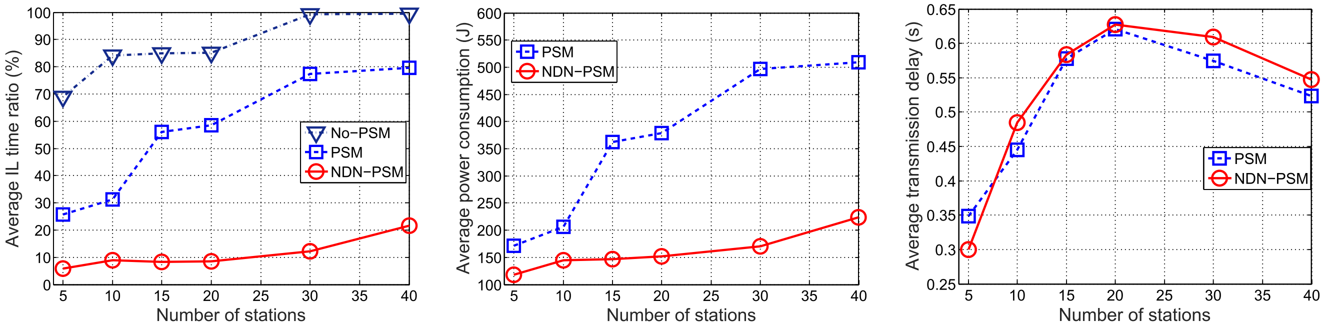
B. *Simulation Results*

We first check the overall performance of *NDN-PSM*. Specifically, we range the number of stations from 5 to 40 with the step of 5, and each of them has the transmission rate of 24 Mbps. In addition, we fix the *CW* to 256, and the T_{LI}^{L} and T_{LI}^{D} to 1 BI and 3 BIs, respectively.

Cutting Down Idle Listening Time. Fig. 10 (a) shows the average idle listening time ratio of all stations, where No-PSM scheme means the PSM functions are disabled. We have the following two major observations. First, the current PSM is not as effective as *NDN-PSM* in reducing IL time. For instance, when there are 40 stations, the PSM can only reduce the IL time ratio from 99.5% to 80% while our *NDN-PSM* is able to cut down the IL time ratio to as low as 22%, which enhance the performance by nearly three times. Second, compared with the PSM scheme which is heavily influenced by the number of stations, our *NDN-PSM* is robust enough to fend against the dense station contending impacts. Specifically, when the number of stations increases from 5 to 40, the average IL time ratio increases dramatically from 28% to 80% in the PSM scheme, while the ratio increases slightly from 8% to 22% in our *NDN-PSM*.

Reducing Power Consumption. Fig. 10(b) shows the average power consumption when changes the number of stations, and we can easily observe that the proposed *NDN-PSM* scheme is rather effective to reduce the total power consumption when compared with the PSM scheme. For instance, when the number of stations is 30, the average power consumption of each station is about 500 J in the PSM scheme while in the proposed *NDN-PSM* scheme, the average power consumption is only 165 J, which is reduced by 56% of power consumption. Additionally, we can also observe that the side impact of channel contentions is well restrained in the proposed *NDN-PSM* scheme, as its average power consumption does not increase obviously as that in the PSM scheme when the number of stations increases.

Comparable Transmission Delay. Fig. 10(c) shows the average transmission delay in both two PSMs when changes the number of stations. It can be seen that the average transmission delay of two PSMs is very close with each other and the performance gap is negligible. For example, when the number of stations is 30, the average transmission delay is about 0.58 and 0.61 ms in



(a) (b) (c)

Fig. 10. Overall performance results. (a) Average IL time ratio. (b) Average power consumption. (c) Average transmission delay.

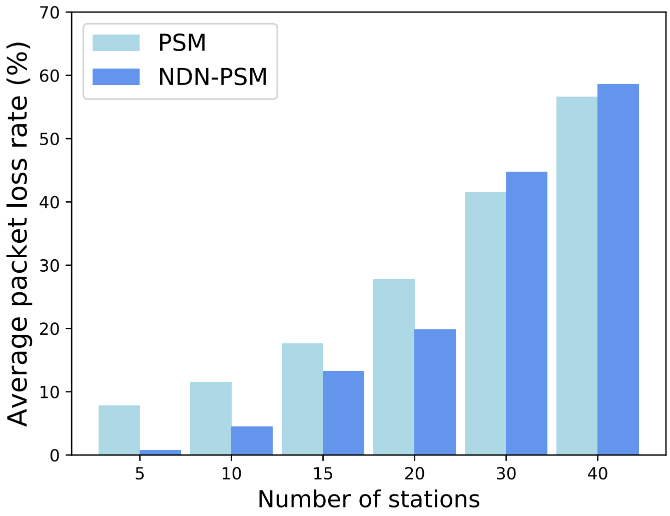


Fig. 11. Average packet loss rate.

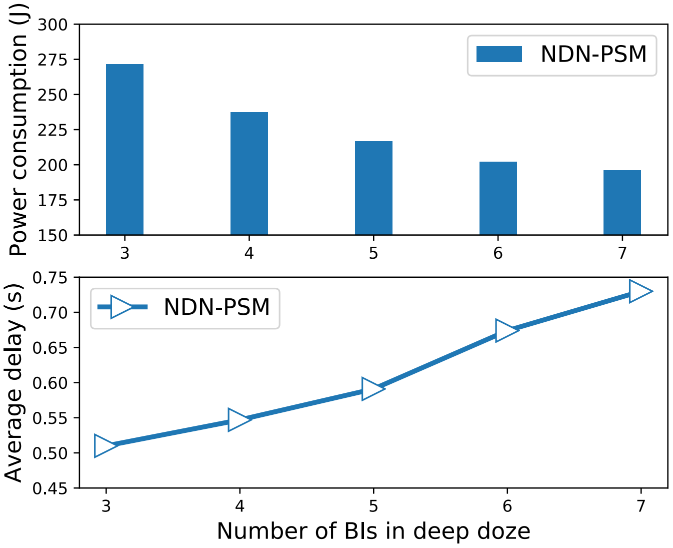


Fig. 12. Impact of listening intervals.

the PSM and *NDN-PSM* scheme, respectively, increasing only by 5%. Normally, when the number of stations increases, the average transmission delay increases in both two PSMs due the channel contention. However, we can see that when the number of stations is larger than 20, the average transmission delay degrades in both two PSMs. It is mainly because that when the number of stations is extremely large, many requested packets fail to come back due the congested channel, which cannot be counted and therefore pull down the average transmission delay.

Two-Sided Packet Loss Rate. We plot the average packet loss rate in both two PSMs when varies the number of contending stations in Fig. 11, and we can have the following three major observations. First, the average packet lose rate in two PSMs are very close with each other regardless of the number of stations. Second, in both two PSMs, the average packet loss rate increases dramatically as the number of stations increases. Third, we can find that the proposed *NDN-PSM* outperforms the PSM scheme when the number of stations is small (e.g., smaller than 20) while performs worse than the PSM scheme when the number of stations becomes large (e.g., larger than 30). It can be explained in two-folds. When the number of stations is small, meaning the light channel pressure, stations would frequently go into the Sleep state in PSM, in which the station sleeps for a long duration, missing the pending data. However, in *NDN-PSM* scheme, stations would go to the light doze state if there is the pending data, in which the station sleeps for a short duration without missing the pending data. In contrast, when the number of stations is large and the channel is heavily congested, stations in the proposed *NDN-PSM* scheme would frequently go to the deep doze state due to the contention failures while stations in the PSM scheme always stay in the IL state waiting for the channel medium.

C. *Impact of Listening Intervals (LI)*

With the overall performance guarantee, we then investigate the impact of LI on *NDN-PSM* performance. Specifically, we fix the T_{LI}^{L} to 1 BI and varies the T_{LI}^{D} from 3 to 7 BIs.[2]

Figure 12 shows the average power consumption and transmission delay when vary the value of T_{LI}^{D}. Distinctly, when the interval of T_{LI}^{D} increases, more power consumption can be saved while the transmission delay could be also prolonged. This

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[2] Note that, as in IEEE 802.11 standard, the AP will disassociate the connection to the station if there is no any response from the station within 8 BIs, we set the T_{LI}^{D} to be no more than 7 BIs.

is reasonable as the transmission could only happen when the station is in the awake state. However, we can see that when the interval of T_{LI}^{D} is no more than 5 BIs, the average power consumption degrades dramatically while the average transmission delay increases slightly as the interval of T_{LI}^{D} increases. In contrast, when the interval of T_{LI}^{D} is larger than 5 BIs, with the T_{LI}^{D} increasing, the average transmission increases dramatically while the average power consumption degrades slightly. Specifically, the average power consumption reduces from 272 to 216 J and the average transmission delay only increases from 0.51 to 0.59 s when the T_{LI}^{D} interval increases from 3 to 5 BIs. However, when the T_{LI}^{D} interval increases from 5 to 7 BIs, the average transmission delay increases from 0.59 to 0.73 s while the average transmission delay only reduces from 216 to 196 J. This indicates that it is better to set the T_{LI}^{D} to be between 3 to 5 BIs.

D. *Impact of Caching*

In NDN, caching is a significant advantage, whereby stations can fetch interested packets from nearby stations without multiple hops relaying, which can further benefit *NDN-PSM*. In this subsection, we briefly demonstrate the efficacy of using cache in *NDN-PSM*. Specifically, the CS size is set to be 10000 packets and each station adopts the Least recently used cache replacement policy. To investigate the performance in different traffic densities, we vary the Interest transmission frequency (ITF) from 5 to 50 packets/s in *ConsumerCbr* model.

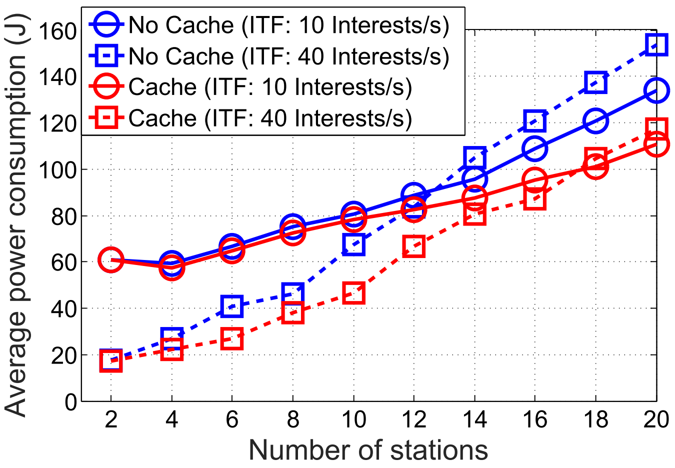
Figure 13 shows the caching-aided *NDN-PSM* performance, in which we vary the number of stations and ITF, respectively. From Fig. 13(a), we can see that with the number of stations increasing, the average power consumption increases accordingly in all settings, which is mainly caused by the underlying channel contentions. However, no matter how the number of stations changes, caching can always enhance the *NDN-PSM* performance. In addition, with more stations, the performance gap between Cache and No Cache schemes becomes more obvious since more stations could benefit from the caching. Fig. 13(b) further verifies the observation, in which the cache-aided *NDN-PSM* scheme always enhance its performance regardless of the underlying traffic densities. For instance, when the ITF is 25 packets/s, without cache, the average power consumption is about 140 and 65 J when the number of stations is 20 and 10, respectively, while when the cache function is enabled, the average power consumption can be reduced to 110, and 50 J, respectively, reducing by 20% power consumption.

VII. RELATED WORKS

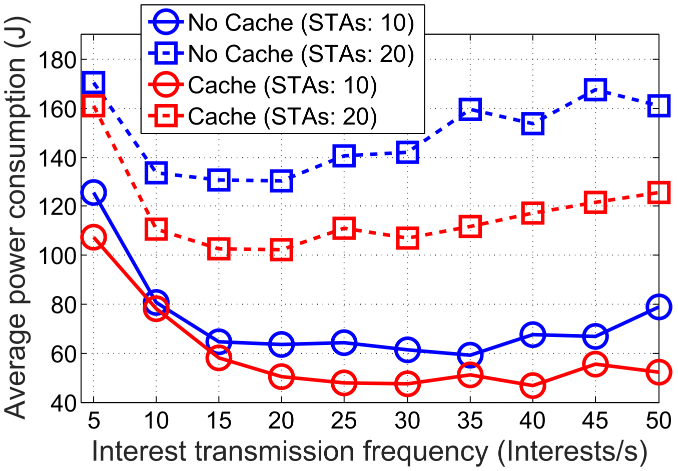
We first introduce some power saving mechanisms adopted in the IEEE 802.11 standards. Then we focus on studies of reducing the power consumption of IL.

PSMs for IEEE 802.11 family. To improve energy efficiency and quality of service (QoS), many power saving mechanisms have been proposed [11], [19], [29]–[33]: Unscheduled Automatic Power Save Delivery (U-APSD), Power Save Multi-Poll (PSMP), Spatial Multiplexing Power Save (SMPS), and Target Wake Time (TWT). U-APSD is an enhanced PSM which transmits a trigger frame at any time to retrieve the data frame from AP. However, when the trigger frame is frequently transmitted, it may increase collision and power consumption. PSMP is a scheduling-based power saving mechanism which allows an AP to schedule downlink and uplink transmission time for multiple stations in a single frame. However, as the number of stations increase, the overhead and the implementation complexity of PSMP increase significantly. Moreover, if the PSMP frame is corrupted or awake on wrong time, the scheduled downlink and uplink time may be wasted. Similar to PSMP, SMPM only keeps one radio of station in the working state and the rest in the Sleep state. The AP will wake up station's radio through RTS, and station will inform AP through CTS that radio has been restored to working state. TWT is a routine and schedule for sleep is permitted by the AP to the associated stations, which allows stations to manage activity by scheduling stations to operate at different times.

Reducing the power consumption of IL. Another cluster of research efforts have been focused on energy saving of IL [27], [34], [35], which can be classified into two categories, i.e.,



(a)



(b)

Fig. 13. Caching-aided *NDN-PSM* performance. (a) Power consumption vs. stations. (b) Power consumption vs. ITF.

reducing the energy consumption in IL state [10], [36]–[38] and reducing the time of IL state [27], [34]. In [10], the proposed E-MiLi mechanism adaptive downclocks the radio during IL, and reverts to full clock rate when an incoming packet is detected or a packet has to be transmitted. The mechanism in [39] detects non-intended frames based on the information of MAC header. A checksum field is proposed to be added in the MAC header to decrease the probability of false detection. In order to reduce the energy consumption of IL, the proposed mechanism in [27] combines three schemes: Firstly, the downclocking scheme to reduce the energy consumption in the station overhearing non-intended frames. Secondly, the frame aggregation scheme extends the semi-sleep time and decreases the channel sensing and accessing overhead per frame. Lastly, the contention window control scheme decreases collisions and avoids unnecessary retransmissions.

In summary, these solutions are based on end-to-end protocols, which may increase the IL time and energy consumption since the pending packets cannot be well predicted. However, *NDN-PSM* has a finer-grained mechanism to make the station stay in doze state with the PIT status information.

VIII. CONCLUSIONS AND FUTURE WORK

In this paper, we have designed a new PSM under NDN architecture, named as *NDN-PSM*, to improve energy efficiency for WLAN. Fine-grained power states have been devised to precisely map to the underlying data arriving states, and a smart channel contention mechanism has been integrated to avoid invalid contentions. In addition, we have established the power consumption model for the proposed *NDN-PSM*, and theoretically analyzed and verified its performance. At last, we have implemented *NDN-PSM* in NS-3 by adopting the ndnSIM module, and the simulation results have demonstrated its efficacy in energy consumption saving. For the future work, we will develop the rate adaptation algorithm and joint schemes (such as downclocking scheme, and contention window control scheme) to further enhance the performance of *NDN-PSM* under dynamic network environments.

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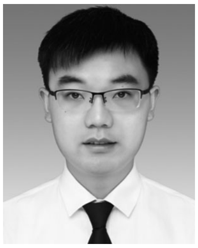

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