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Analysis of PS Protocols Using Markov and Cluster Model in 802.11 WLANS

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Abstract— In recent years, a series of power saving (PS) protocols has been proposed in the family of 802.11 standards to save energy for mobile devices. To evaluate their performance, many works have been carried out on test beds or simulation platforms. However, till now, there is a lack of accurate theoretical models to analyze the performance for these protocols. In an effort to fill this gap, we present a Markov chain-based analytical model and cluster model in this paper to model these PS protocols, with its focus on multicast services in wireless LANs. The proposed analytical model successfully captures the key characteristic of the power saving system: the data delivery procedure starts periodically at the previously negotiated time, but ends at a rather random time with its distribution depending on the end time of data delivery in the last delivery period as well as the arrival rate of incoming traffic. In the situations with light to moderate traffic loads and under the Poisson assumption for incoming traffic, the amount of data delivered between consecutive delivery periods possesses the Markov property, which builds up our Markov chain-based model. For incoming traffic with long-range dependence (LRD), a multistate Markov-Modulated Poisson Process (MMPP) is used to approximate the traffic, making the analytical model valid in more general cases. We verify our model by simulations on ns2 and the results show that the model can faithfully predict the performance of these PS protocols over a wide variety of testing scenarios.

Index Terms—802.11 power saving, multicast, Markov model.

I. INTRODUCTION

With the maturity of 802.11 technologies, wireless LAN has become ubiquitous in providing continuous Internet access for both public offices and private residential areas. Yet, since the capability of most portable devices is limited by the batteries, energy conservation has become an increasing concern for design and implementation of new network protocols.

Many 802.11 wireless network interfaces have two working states, awake state and sleep state. In the awake state, the radio is powered up and the wireless interface can perform data transmission or reception, or just stay in idle and wait. In the sleep state, on the contrary, the radio is turned off and the wireless interface can not detector sense the network behaviors of others. Wireless interface in awake state usually consumes an order of magnitude more power than that in the sleep state. The major task of power management is to choose proper time and sequence of state transitions between the two working states. A good solution should wake up the wireless interface at the proper time for communication, and allow it enter into sleep state to save energy if no traffic is direct to it.

A series of power saving (PS) protocols has emerged in the 802.11 standards to conserve energy in 802.11 wireless LANs. In the seminal standard 802.11, a power save mode (PSM) is proposed for low powered mobile devices. The PSM uses the periodical beacon messages to disseminate traffic information among the PS mobile stations. The access point (AP) buffers all incoming data for those PS stations and delivers the data to them at the negotiated time periods when those stations are in awake state. The major disadvantages of 802.11 PSM are that 1) its data retrieval procedure for unicast service is not efficient and 2) it suffers impact of background traffic. Subsequent to the 802.11, in 802.11e, the PSM is enhanced by a new scheme named automatic power save delivery (APSD). The APSD improves the efficiency of PSM for unicast services by allowing multiple frames delivered at the reception of one request. Later on, in 802.11v, the efficiency for multicast services is enhanced by the flexible broadcast/multicast service (FBMS), which is able to differentiate different multicast streams so as to mitigate the impact of background traffic. Recently, in 802.11n, a power save multipoll (PSMP) is proposed as a solution to effectively remove the impact of background traffic for both the unicast and multicast services.

This paper aims to provide a theoretical framework for these PS protocols proposed in the aforementioned standards, with emphasis on multicast services in wireless LANs. A theoretical model is of particular use for understanding the performance of a PS protocol, as well as guiding the design of new PS protocols. However, analytical modeling of PS protocols in contention-based CSMA networks is challenging because the functioning of a PS protocol usually involves multiple aspects, including medium access control mechanisms, incoming traffic patterns, and the interactions between AP and distributed PS stations. So far few works were carried out in this area. Lei and Nielsen model, the data delivery procedure in 802.11 PSM by an M/G/1 queue with bulk service. This model assumes that all PS data arriving in the middle of data delivery procedure are buffered until next beacon period (offline delivery policy). This assumption does not hurt the results when we only consider the power efficiency, but increases the traffic delay and jitter. In practice, the 802.11 PS protocols employ an online delivery policy that also delivers the data arrived in the middle of the delivery procedure, thus, having shorter downlink delays than the offline delivery policy. There are also some analytical models in other network paradigms, such as sensor networks, ad hoc networks, 802.16e WiMAX, and UMTS systems. However, these models cannot be applied for analyzing PS protocols in 802.11 wireless LANs due to different PS mechanisms in those network paradigms.

The main contribution of this paper is a novel Markov chain model to analyze the performance of the PS protocols for multicast services in wireless LANs. The model successfully captures the key characteristic of these PS protocols: the data delivery procedure starts periodically at the previously negotiated time, but ends at a rather random time with its distribution depending on the end time of data delivery in last delivery period as well as the arrival rate of incoming traffic. Under the assumption of poisson traffic and without "delivery overflow," the amount of data delivered between consecutive delivery periods possesses the Markov property. Based on this model, we derive the power consumption of a station and average network delay of a multicast stream. We further discuss the applicability of our model in analyzing a PS system for a general traffic with long-range dependence (LRD). By modeling the LRD traffic through multistate Markov-modulated poisson process (MMPP), we show that our model can be extended to analyze LRD traffic. Moreover, although our emphasis is multicast services in this paper, we note that our approach can also be extended into unicast services. The limitations of our current model are that it did not consider the uplink traffic, and it is not appropriate for modeling a PS system under heavy traffic loads.

We first validate the analytical model via simulations on network simulator ns2. Comparison between analytical and simulation results shows that the proposed model is able to predict the distribution well, particularly for light to moderate traffic loads. We further study the applicability of this model in evaluating the performance of three PS protocols: 802.11 PSM, 802.11e FBMS, and 802.11n PSMP. Results show that the analytical model is capable of correctly analyzing the energy efficiency and network delay for a variety of testing scenarios, and is able to identify key performance trade-offs such as how to balance the network delay and energy consumption. The rest of the paper is organized as follows: Section 2 provides an overview of PS protocols in the family of 802.11 standards for multicast services and related research works in this area.

II. BACKGROUND AND RELATED WORK

In this section, we give a brief introduction to several power saving protocols for multicast services in the series of 802.11 family of standards, followed by an overview of related work in the area of power management modeling.

802.11 PSM for Multicast Services

A PSM is defined in the 802.11 specification for power management. In this mode, the AP temporally buffers incoming frames destined for mobile stations in PSM, and periodically announces its buffer status through the traffic indication map (TIM) contained in each beacon. The TIM structure conveys traffic information that informs each station whether or not there are data pending for it at the AP. The mobile station wakes up periodically to listen to the beacons and parse the TIM structure. In the broadcast/ multicast (B/M) case, the presence of buffered B/M frames at the AP is indicated by setting the B/M traffic indication bit in the delivery TIM (DTIM), which is a special TIM, sent out at a fixed number of beacon intervals. All B/M frames buffered at the AP are delivered immediately after the beacon frame containing DTIM. In the delivery procedure, each B/M frame uses the MoreData bit in the header to indicate whether the AP has more buffered B/M data for PS stations. A value of 0 for MoreData bit concludes the data delivery procedure and all data arriving before this time point should be delivered, and only data after this time point should be buffered until the next DTIM (online delivery policy). As opposed to the normal continuous active mode (CAM), a mobile station in PSM can have opportunities to turn its network interface off to save energy when it has no data pending at the AP. For light to moderate traffic load, this legacy PSM can greatly reduce the energy consumption at the mobile station.

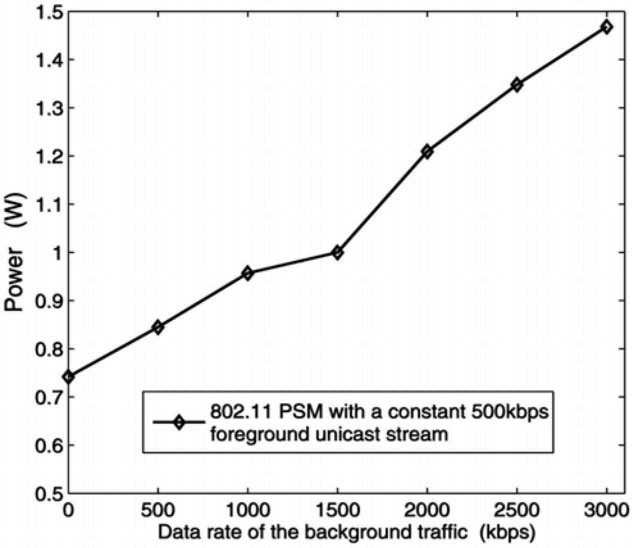


Figure.1 Measured power consumption of PDA as a function of the data rate of the background multicast traffic. The foreground traffic is a unicast UDP stream with rate fixed at 500 Kbps, while the background traffic is a multicast UDP stream with its rate varying from 0 to 3 Mbps.

However, for the 802.11 PSM, this power saving can only be achieved in the absence of background traffic. In this paper, for a considered station A, we define the traffic that is destined for station A as the foreground traffic, and all other traffics that are not destined for station A as the background traffic. In our prior work, we studied the impact of the background multicast traffic on the performance of the 802.11 PSM on commercial PDAs. Figs. 1 and 2 are two representative results. Fig. 1 shows the impact of the background multicast traffic on the power consumption of the PDA. Although the data rate of the foreground traffic is kept constant on the client PDA, its power consumption rises linearly with the increase of the background multicast traffic load. In Fig. 2, a comparison study has been conducted to evaluate the impact of background multicast traffic among three cases: CAM, PSM without background traffic, and PSM with a 1.5 Mbps background multicast traffic. The gap between these curves demonstrates that the presence of background traffic causes a jump in power consumption even if 802.11 PSM is applied.

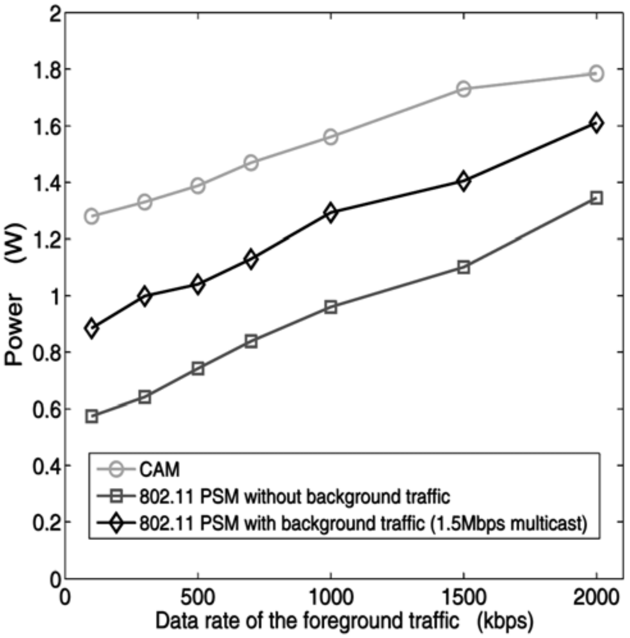


Figure. 2 Comparison of power performance among three cases: CAM, PSM with and without background traffic. Both the foreground and background (if any) traffics are multicast UDP streams, and the foreground stream increases from 100 Kbps to 2 Mbps for each case.

The reason for this sizable power increase induced by background traffic is that the 802.11 PSM uses only one bit in the traffic indication map to indicate the presence of buffered B/M data at the AP. Therefore, it does not provide sufficient granularity to distinguish multicast data from broadcast data, as well as multicast data for different groups. As the consequence, a mobile station has to receive all the broadcast and multiaddressed data. Although some of these receptions are not destined to it and have to be dropped at the higher layer of networking stack. This places extra burden on the mobile station's energy consumption and degrades the efficiency of 802.11 PSM.

FBMS in 802.11v

To improve the efficiency of 802.11 PSM against background multicast traffic, a new mechanism called FBMS is introduced in 802.11v draft. In FBMS, different B/M streams can be scheduled to be delivered at different beacon periods. This is achieved by assigning different DTIM counters for different B/M streams. A counter decrements by 1 at each DTIM period. Upon expiry of the counter (reaching zero), the AP schedules data delivery for the corresponding B/M stream. A station can wake up only at its DTIM periods to receive its data and sleep during other DTIM periods. Different from 802.11 PSM, the end of data delivery for a B/M stream is indicated by setting the End of Service Period (EOSP) bit in the frame header.

Overall, the FBMS improves the 802.11 PSM in two aspects. First, it differentiates the B/M streams by adoption of stream IDs. Second, it schedules different B/M streams at different DTIM periods by arranging the DTIM counters at the AP.

PSMP in 802.11n

In fact, FBMS not only has prolonged delivery delay but also suffers impact from the uplink data transmissions because of the contention between uplink and downlink traffics. To overcome these issues, a PSMP protocol is proposed in 802.11n. It reduces network delay by considering differentiated data scheduling with a smaller timescale, for example, a sub multiple of one DTIM period. It relies on the AP to schedule both uplink and downlink data to transmit at the appointed time periods so that the data delivery procedure for a stream cannot be interrupted by transmissions of other stations. The key idea of the PSMP is that it allows AP to assign a private transmission period dedicated to each station and schedules all stations to deliver their data at the appointed time periods. Similar to 802.11v FBMS, it uses EOSP to indicate the end of data delivery for a stream. The PSMP provides a good solution to overcome the impact of background traffic, however, compared to the 802.11 PSM and FBMS, the overhead of the management frames increases considerably and the mechanism to maintain the uplink transmissions is fairly complex. As revealed in our analysis in this paper, the power performance of PSMP can often be worse than FBMS because of its frequent state transitions of network interface.

Related Work

There are several theoretical studies on the modeling of power saving systems. The data delivery procedure between listen intervals is modeled by an M/G/1 queue with bulk service. It treats all PS data that arrived at AP in last listen interval as a bulk that is assumed to be delivered at the beginning of the next listen interval. The time differences to deliver these PS data in a listen interval are neglected to ease the delay analysis. In addition to the M/G/1 model, the authors also consider a D/G/1 model, which characterizes the data arriving at AP as batch arrival process with interarrival time of batches equal to the listen interval. Intuitively, treating the data arriving within a listen interval as a bulk or batch (hence, all data arrived in a listen interval are buffered until next listen interval) should simplify the analysis. However, it does not capture the essential behavior of 802.11 PSM in practice. In 802.11 PSM, the data arrived before the conclusion of data delivery procedure in a listen interval will be delivered immediately within the same interval, and only those data that arrived after the conclusion of delivery procedure will be buffered until the next listen interval. This delivery policy is called the online delivery policy, as opposite to the offline delivery policy. Our prior work shows that a PS system with an online delivery policy is much more efficient, particularly in terms of network delay than the offline delivery policy. Therefore, most PS protocols in 802.11 wireless LANs employ the online delivery policy to reduce network delays. In contrast, the model proposed in this paper accurately captures the “online delivery policy” based on the concept of busy period in queuing system analysis. Moreover, our model can also be extended to cope with a general traffic with LRD.

In addition to these analytical models, there are many research works on the design of power management strategies in wireless LANs. Simunic et al. proposed a time-indexed semi-Markov decision process (TISMDP) model to derive an optimal policy for system-level power management. A bounded slowdown (BSD) protocol is presented to provide bounded delay for Web-like applications. Anand et al implemented a self-tuning power management (STPM) module that adjusts the power saving schemes with application hints. We addressed the impact of background traffic on 802.11 PSM and proposed a time-slicing-based solution to mitigate this impact. Recent works focused on improving the performance of 802.11 PSM for QoS-aware applications such as voice over IP (VoIP). In addition, there are experimental works aiming to provide insights for 802.11 PSM performances in test beds.

III. THE ANALYTICAL MODEL

In this section, we present the analytical model for the 802.11 family of power saving protocols. We first give our basic assumptions, and then we describe in detail the proposed Markov model.

Basic Assumptions

To make the problem tractable and ease our analysis, we have made the following assumptions in our model:

A1. Similar to many other analytical models in our model, the interarrival times of each incoming B/M stream are assumed to be exponentially distributed. That is, each stream should be a poisson flow. Although poisson arrival of incoming traffic is a strong assumption, it is still useful for performance evaluation since the Internet traffic can be modeled as superposition of multiple poisson flows of different rates by techniques like MMPP.

A2. We assume that each data frame has the same payload size L (bytes) and enjoys the same medium access delay t_B. Hence, the time to deliver a single PS frame from AP to a mobile station is constant. L and t_B can also be treated as the averaged estimation of payload size and access delay. Let denote the average time to deliver one single multicast frame, it can be expressed as (note that there is no prefix such as RTS/CTS or postfix such as ACK for multicast services)

$$\tau = t_B + t_{preamble} + 8L/R_{phy},$$

Where $t_{preamble}$ and R_{phy} are the preamble time and physical data rate, respectively. This assumption is not necessary for the Markov-chain-based model, but it simplifies the computation in our model.

A3. During the period when B/M data are delivered, there are no attempts of data transmissions initiated by other stations (except AP). That is, currently, we do not consider the impact of uplink traffic or non- PS traffic in our model. This assumption is reasonable for multicast services, since in the 802.11 family of protocols, B/M data are usually given a higher priority over unicast data during service (note that in PSMP, this assumption is always true because no interruptions occur in the data delivery procedure).

A4. When PS data cannot be delivered within a delivery period (DP) because of limited time/ bandwidth, which we call a “delivery overflow”, happens, all these overflowed data are to be discarded at the end of this DP. Thus, these “overflow” data would not affect the data delivery of the next DP. This assumption implies that our analytical model is only applicable for light to moderate traffic situations and not suitable for heavy traffic cases. Nevertheless, this is reasonable as power saving is not effective in heavy traffic conditions.

Markov Chain Model

Although each PS protocol differs in the lengths of delivery periods and in their ways to deal with multiple multicast streams, they all can be characterized by a general framework as shown in Fig. 3. In this framework, the delivery procedure of a single frame is treated as an atomic operation, lasting for a fixed period of τ as we stated in assumption A2. All PS B/M data are delivered periodically in each DP. A delivery period may be a DTIM period in 802.11 PSM, an integer multiple of DTIM period in 802.11v FBMS, or a periodical service period in 802.11n PSMP.

At the beginning of a DP, the AP broadcasts a notification message (may be a beacon for 802.11 PSM and FBMS or a PSMP frame for PSMP) to the network. The message contains traffic information for data delivery, such as whether there are pending B/M data at the AP. A mobile station receiving this message determines whether there are PS data for it in this DP by parsing the information element in the message. If so, the station remains awake until a received frame has explicitly indicated the end of the data delivery for the current period by a cleared MoreData field or set EOSP bit in the frame header; otherwise, the station can enter into sleep state immediately until the next DP.

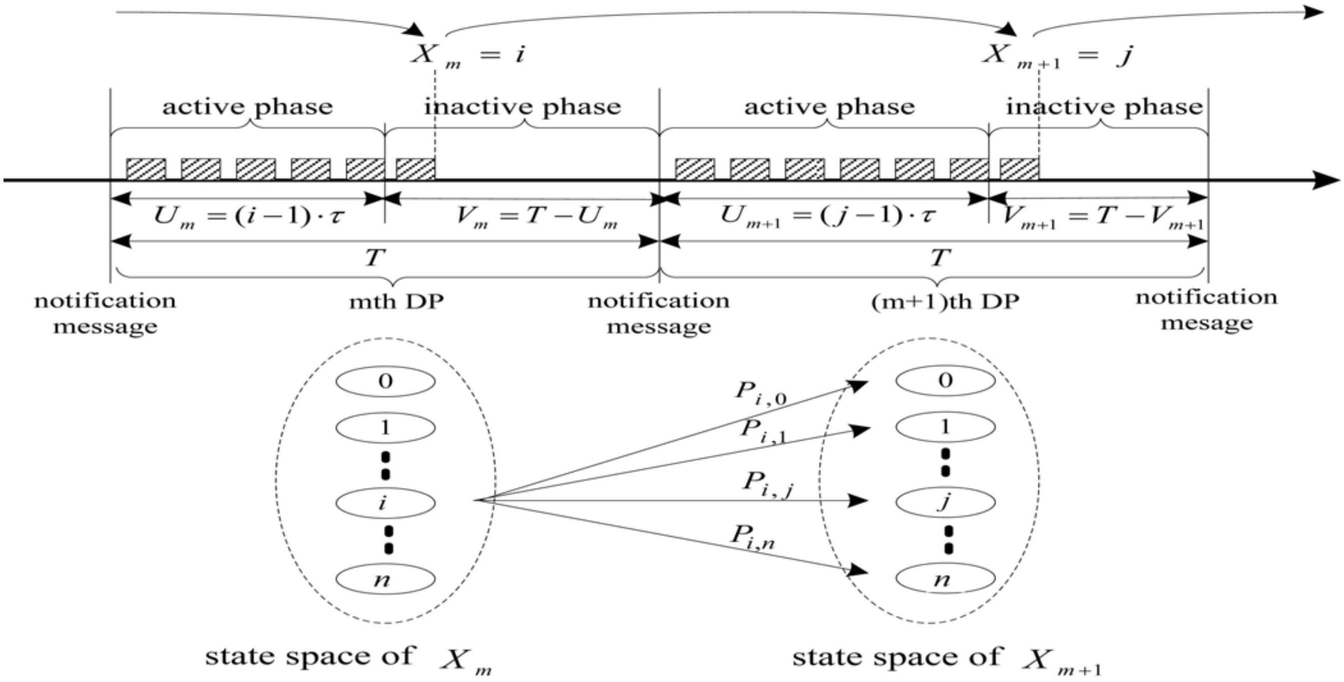


Figure. 3 A unified frameworks and Markov chain model.

In addition, there are two rules that should be followed for the data delivery procedure at the AP as follows:

R1. Once a frame (called the last frame) has indicated the end of the data delivery procedure (by a cleared MoreData field or a set EOSP bit) for a stream, then all subsequent frames arriving after the transmission of that frame should be temporarily buffered until the next DP. Since in practical implementation, the setting of MoreData or EOSP bit for a frame occurs at the time when putting it into the back off queue, clearly these frames arriving during the delivery time of the last frame should also be counted as buffered data for the next DP.

R2. All frames arriving before the delivery of the last frame are delivered in the current DP. This is true since at the time when setting the MoreData or EOSP field of the last frame, there should be no other pending frame belonging to the stream at the AP's buffer. Otherwise, the AP cannot set a "noData" tag to the last frame.

Therefore, the last frame in a DP divides the DP into two separate phases, named as inactive phase and active phase, respectively, in this paper. In the inactive phase, all incoming PS data are buffered and no data delivery occurs, while in the active phase, all PS data backlogged since last inactive phase are delivered. The exact boundary between the two phases is the epoch when setting the MoreData or EOSP bit for the last frame, which occurs at the beginning of the delivery of last frame.

Consider B/M streams M0 with an arrival rate of λ, and suppose that i frames are served in the mth DP, where m is the index of the current DP. Let Um and Vm denote the duration of the active phase and inactive phase within the mth DP, respectively. The duration of the DP is denoted by $T = U_m + V_m$. Let $N(t)$ be the number of incoming PS frames arriving within the period (0, t) for stream M0.

Now we have established a one-dimensional discrete time Markov chain to model the data delivery procedure for stream M0. This Markov chain should have unique stationary probabilities for each state $\{\pi_0, \pi_1, \ldots, \pi_n\}$ which can be further derived by solving the following equations:

$$\begin{cases} \pi_j = \sum_{i=0}^{n} \pi_i \cdot P_{ij}, \\ \sum_{j=0}^{n} \pi_j = 1. \end{cases}$$

Note that $\pi_j (0 \leq j \leq n)$ represents the stationary distribution of the amount of data delivered in a DP. It gives the performance measure of a PS protocol on a finer grained level than general performance metrics such as power consumption and network delay.

Cluster Model

Clustering is a process that divides the network into interconnected substructures, called clusters. Each cluster has a Cluster Head as coordinator within the substructure. The proposed algorithm is a very quick clustering algorithm and creates minimum clusters with maximum member node in each cluster. The simulation results show that the proposed algorithm provides better performance in terms of the number of formed clusters and average number of transition (state change) on cluster heads when compared to that of other weight based algorithms such as Weighted Clustering Algorithm (WCA).

In this section we describe clustering protocol. In the proposed protocol we allocate a weight to each node. The weights are in three groups, that each group specifies the credit measure of a node to becoming head.

Cluster Modules

a) Cluster Formation:

Initially all nodes are in ISOLATED state. Then each node broadcasts LIVE message to declare itself and to have knowledge of its neighbor nodes, which can be used to calculate its weight.

b) Cluster Maintenance:

In order to maintain a cluster, each CH broadcasts the LIVE message every Ti seconds (Ti >> Te) within the cluster periodically. NORMAL and GATEWAY nodes also broadcast the LIVE message every 2Ti seconds.

c) Routing:

Routing is executed according to the basic of on demand. When a node wants to send a packet it searches the destination node’s address in its cache, and if found a valid route to that node, it starts sending packets. Otherwise, if it did not find a valid route to the destination node, it should deal wait the act of discovering routes.

Remarks

We have the following remarks regarding our analytical model.

First, among the four assumptions, assumptions A1 and A4 ensure the Markov property for the data delivery procedure in consecutive DPs, and that builds our Markov model. Note that, for traffic models based on MMPP, the Markov property is also preserved, which indicates that this model can be readily extended to analyze the LRD traffic because LRD traffic can be accurately approximated by superposition of multistate MMPP sources. The only difference is the transition probability matrix P should be calculated by theory of MMPP / D/1 queue instead of M/D/1 queue.

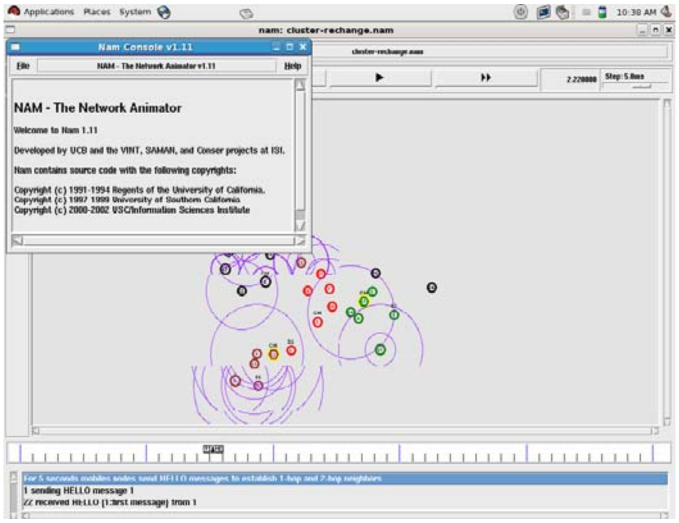
Second, in assumption A2, we abstract the underlying medium access detail which usually involves randomized back off procedure as time-invariant process. This is reasonable since for multicast services employing random back off, the contention window size CW does not vary with time and no data retransmission occurs. It is thus easy to estimate the average back off time tB. This assumption sacrifices system accuracy, but provides significant convenience for computing the analytical results. However, it, by no means, indicates that our model is only valid for such cases. In fact, for time variant cases, this model can still be applied because the distribution of service time does not affect the Markov property of data delivery procedure in consecutive DPs.

IV. PERFORMANCE ANALYSIS

By the Markov model, we can derive the stationary distribution of the number of frames delivered in a DP. In this section, we explain how to use the derived distribution to analyze both the energy consumption and network delay for multicast services in the 802.11 family of power saving protocols.

V. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, comprehensive simulations have been conducted on network simulator ns2 to examine how the proposed analytical model can predict the performance of three power saving protocols: 802.11 PSM, 802.11v FBMS, and 802.11n PSMP. We first investigate the accuracy of our model in predicting the distribution of the number of frames delivered in a DP, and then study both the power consumption P and network delay E(D) between the analytical model and simulation results. To characterize each of these power saving protocols, we vary the key system and traffic parameters, such as the length of DP (T), the traffic rate (λ), and the number of imposed multicast streams (k), and examine their impact on overall system performance.



NAM - The Network Animator

Welcome to Nam 1.11

Developed by UCB and the VINT, SAMAN, and Conser projects at ISI.

Nam contains source code with the following copyrights:

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For 5 seconds mobiles nodes send HELLO messages to establish 1-hop and 2-hop neighbors
1 sending HELLO message 1
22 received HELLO (1:first message) from 1
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Figure. 4 NAM Window

For 5 seconds mobiles nodes send HELLO messages to establish 1-hop and 2-hop neighbors

Figure. 5 Data Transmission between Nodes

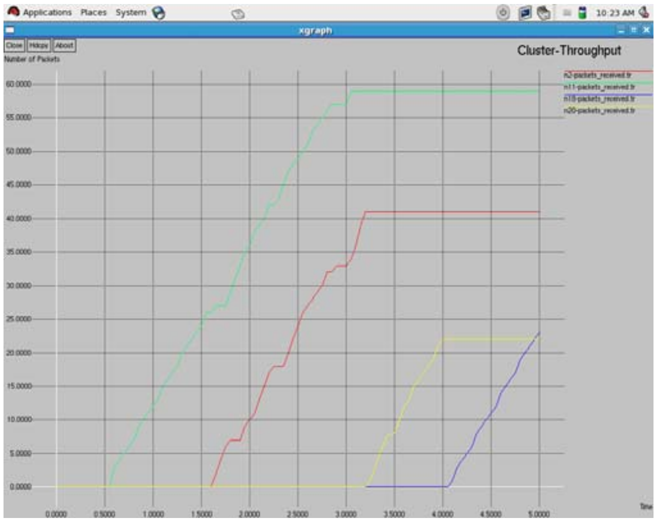

Figure. 6 Cluster Throughput

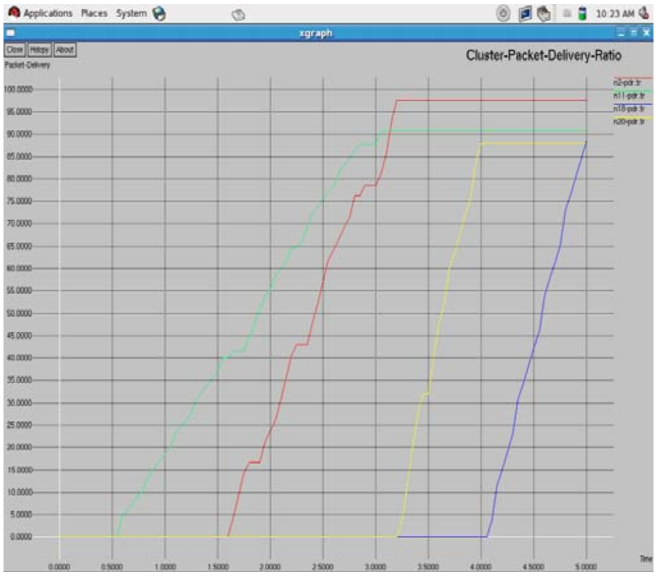

Figure. 7 Cluster-Packet-Delivery-Ratios

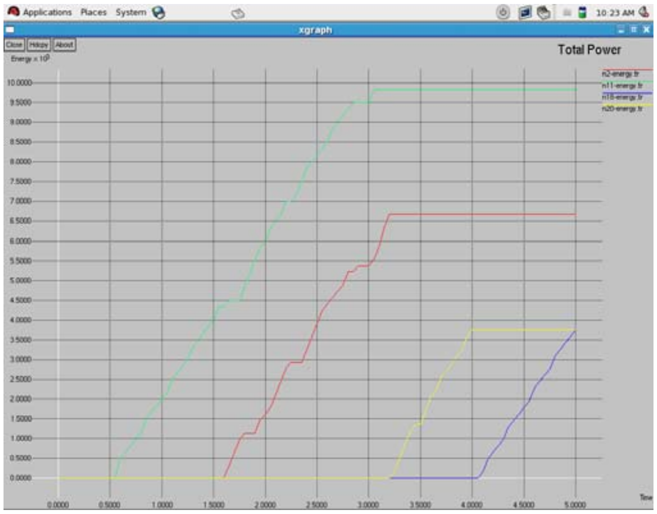

Figure. 8 Total Power

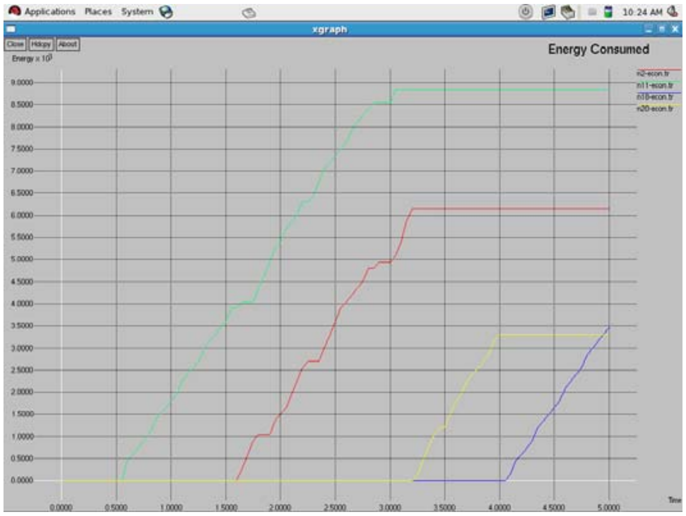

Figure. 9 Energy Consumed

VI. CONCLUSION

In this paper, we proposed a Markov chain model to study the performance of a series of PS protocols in the family of 802.11 standards. Our study emphasizes on the downlink multicast traffic in wireless LANs. Under the assumption of poisson arrival for the incoming PS traffic without "delivery overflow," the amount of delivered PS data between consecutive delivery periods is modeled by a Markov process. Compared with prior analytical models, the novelty of our model is that it successfully captures the online delivery policy employed by all three 802.11 PS protocols. Using this model, we obtained the power consumption of a mobile station and the average frame delay of a multicast stream. The comparison study between the analytical model and the simulation results on ns2 demonstrates that our model can faithfully predict the performance of PS protocols over a variety of testing scenarios. We further extended our model to general Internet traffic scenarios, where MMPP is employed to approximate traffic with LRD. We showed, by example, that a 12-state MMPP could provide a good approximation for a VBR video stream. The primary limitations of this model are that it focuses on the multicast traffic and is valid only in situation with light to moderate PS traffic loads. In our future work, we will extend this model for the analysis of unicast traffic as well as heavy traffic scenarios.

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