Power Save on 802.11ax MAC

Yang Hang

Advisor: K.C. Chen

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Gratitude Institute of Communication Engineering

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802.11 MAC and its Power Save

802.11 MAC–DCF

Before 802.11ac, wifi use a single-user (SU) PHY, i.e., only one node could access at a time.

Distributed Coordination Function (DCF) is a random access mechanism. All nodes including stations (STAs) and access point (AP) need contend to access the channel.

DCF is a simple and flexible mechanism so that it works on unlicensed band.

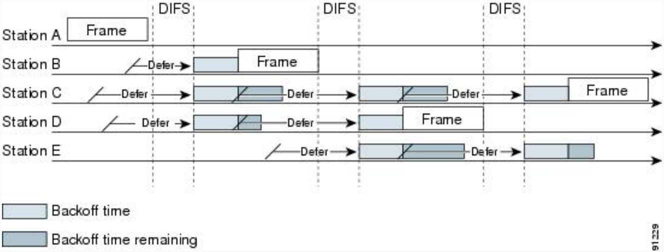


Figure 1: DCF example

Energy Consumption of WiFi

Since most AP is powered with wire, energy consumption of STAs deserves our concern. Several sources of energy waste of a STA are as follows [7].

1. **Idle Monitoring**
2. **Collision** It is serious in dense network.
3. **Overhearing**
4. **Control Packet Overhead** Like RTS/CTS, ACK.
5. **Header Overhead** It is necessary for an unscheduled mechanism.

Actually, all the up-link (UL) transmission is effective, since STAs know UL arrival time once UL packet arrives. Unfortunately, STAs don't know when down-link (DL) packets come. They need stay active all the time to get ready for a DL transmission intuitively.

Working State Occupation[5]

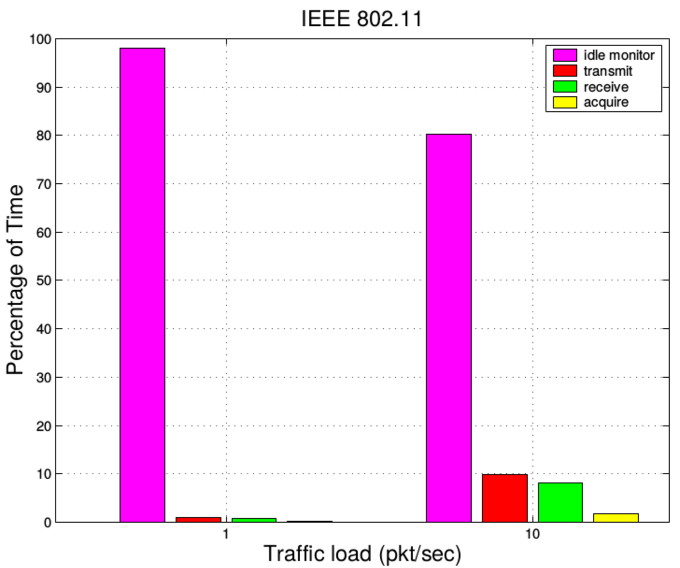


Figure 2: A Node's Dwell Time in Different States

Power Save Mode (PSM) of legacy WiFi

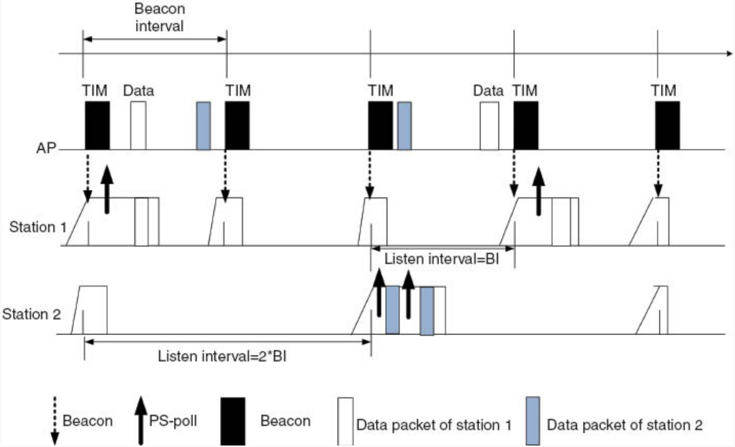
See a successful transmission as a rendezvous between AP and STA.
Three classes of Rendezvous Schemes:

- Synchronous Scheme
- Pseudo-synchronous Scheme, cycled receiver
- Asynchronous Scheme, wakeup radio

Since UL transmission is effective transmission, legacy PSM, called Periodical Listen and Sleep, only concerns about DL transmission. It belongs to **Pseudo-synchronous Scheme**.

Legacy PSM: Periodical Listen and Sleep

Key components: Beacon and Traffic Indicate Map (TIM), listen interval, PS-poll packet.



Difference in 802.11ax MAC

Key Features of 802.11ax MAC

OFDMA helps realize MU PHY in 802.11ax, as a result leading to Trigger-based UL. See figure 3.

DCF doesn't care about UL/DL fairness. Legacy AP is almost equal to STAs on MAC. However, the star topology determines the priority status of AP in BSS. In 802.11ax, UL and DL are both scheduled by AP. **An efficient scheduler** is needed. Here, we focus on the **energy efficiency**. Proposed PSMs for 802.11ax are as following slides.

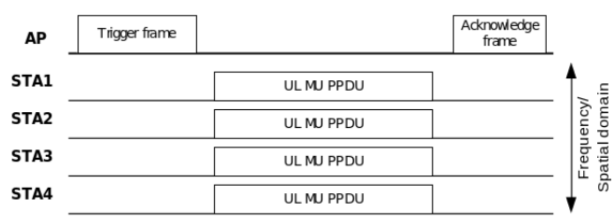


Figure 3: trigger-based MU UL[1]

Passive PS (PPS)

Passive PS save power by turning off its radio until the end of transmission of intra-BSS for others. To realize this mechanism, **BSS color**, **STA identifier**, **UL/DL indicator** are set in HE-SIG-A/HE-SIG-B.

According to [2], an HE STA may enter the Doze state until the end of an PPDU if the following conditions are true:

- same BSS color
- DL but not the same identifier; or UL

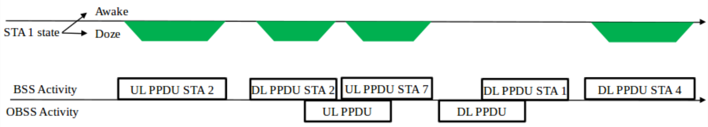


Figure 4: Passive PS for 802.11ax[2]

PS for Random Access (PSRA)

Since trigger frame for random access (TF-R) proceeds the UL transmission, STA couldn't start UL transmission until TF-R arrives. STA could "sleep" until TF arrives. That's the intuitive idea behind PSRA.

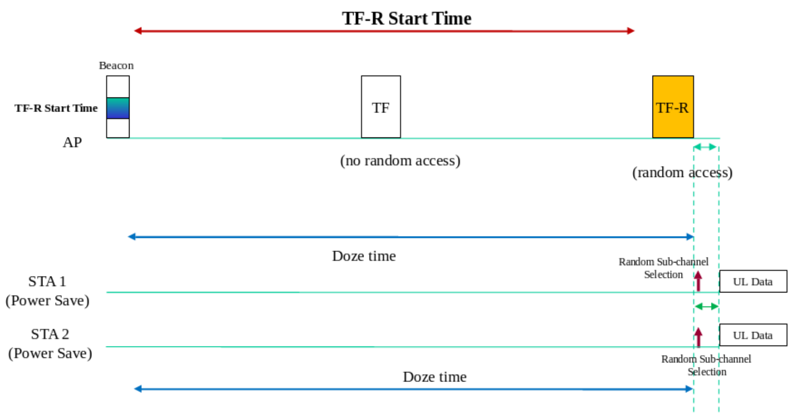


Figure 5: PSRA[3]

Problems of Proposed PSM for 802.11ax

- PPS helps PS by reducing the waste energy on **overhearing**. The heavier loading traffic, the more energy are saved. However, it doesn't help for **idle monitoring**, see Figure 2. Thus, it works as an auxiliary PSM.
- Current PSRA is **not** a complete approach.

Since before 802.11ax, UL is scheduled by STAs themselves. Legacy PSM has been well designed for DL traffic, which still works on 802.11ax. While trigger-based UL is the main difference from legacy 802.11 versions, we will **focus on PS for UL**.

My PS design for 802.11ax UL

My PS design for 802.11ax UL

Since UL is based on triggered frame (**TF**), design as follows:

1. Two kinds of TF are issued here. **TF-R** for request collection, regular **TF** for resource allocation.
2. TF-R is scheduled periodically with well-known period T.
3. Resource Request (**RR**) procedure includes contending and selection. When number of success contending STAs is large, AP has not enough resource to allocate, then selecting some to allocate resource.
4. **More bit** is set when the allocated resource is not enough for the UL traffic.

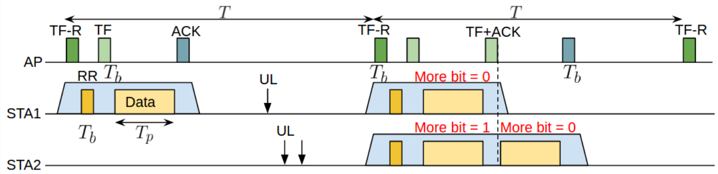


Figure 6: PS for 802.11ax UL

Problem Formulation

Assumption

- No channel fading
- P_{TX} is a constant
- Assume random access for RR with constant contention window
- IFS and TF-R's DCF contending is ignored.
- Poisson Arrival λ for each STA UL

$$E = \triangle_{RX} P_{TX} + \triangle_{TX} P_{RX} + \triangle_{idle} P_{idle} + \triangle_{doze} P_{doze} \tag{1}$$

We only consider UL traffic here. Since IFS and DCF contending are ignored here and STAs know when TF-R will arrive, with PS, STA could wake up only for transmission. That means no idle state. On the contrary, without PS, duration of doze state is replaced by idle state.

$$\text{with PS}: \; \triangle_{doze} = 1 - \triangle_{RX} - \triangle_{TX} \tag{2}$$

$$\text{without PS}: \; \triangle_{idle} = 1 - \triangle_{RX} - \triangle_{TX} \tag{3}$$

$\triangle_{TX}$ and $\triangle_{RX}$ Representation

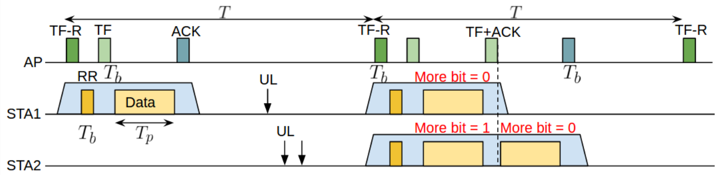
Notations

D^{s}_{TX}: Duration of TX in successful Resource Request (**RR**)
D^{f}_{TX}: Duration of TX in failing **RR**
p_s: prob. of suc **RR**
p_t: transmit prob. of STA

All variables following should be expected value.

$$\triangle_{TX} = \frac{1}{T}[D^{s}_{TX} p_s + D^{f}_{TX}(1 - p_s)]p_t \tag{4}$$

$$\triangle_{RX} = \frac{1}{T}[D^{s}_{RX} p_s + D^{f}_{RX}(1 - p_s)]p_t \tag{5}$$



$D^s_{TX}, D^f_{TX}, D^s_{RX}, D^f_{RX}$

Notations

T_b: time for transmitting a control frame

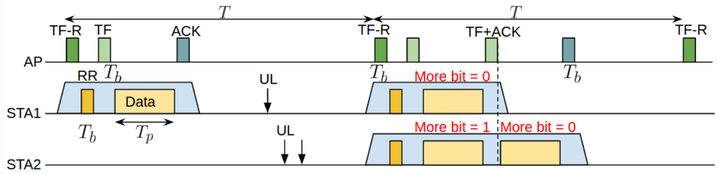
T_p: time for transmitting a data frame under normal data rate

UL: num. of UL packets to be sent in current TF period given suc RR

R: allocated resource (normalized date rate)

$$D^s_{TX} = \frac{UL}{R} T_p + T_b, \quad D^f_{TX} = T_b \tag{6}$$

$$D^s_{RX} = (UL + 2) T_b, \quad D^f_{RX} = 2 T_b \tag{7}$$



Compute UL and R

$$
\begin{aligned}
UL &= \lambda T \sum_{k=0}^{\infty} (1 - p_s)^k \\
&= \frac{\lambda T}{p_s} \qquad (8)
\end{aligned}
$$

$$
R = \frac{n_{ch}}{N_s} \qquad (9)
$$

Notations

UL: num. of UL packets to be sent in the current TF period given suc RR

R: allocated resource (date rate)

n_{ch}: num. of channels

N_s: num. of suc RR STA

p_s: prob. of suc RR

If UL packets are not transmitted in current TF period, it will be deferred to next TF period, as equation 8.

For resource allocation, resource is bandwidth that STA could use. Here, use channel number to represent it.

Compute N_s ,p_s and p_{ss}

$$N_s = \min\{n_s, n_{ch}\} \tag{10}$$

$$p_s = p_{sc} p_{ss} \tag{11}$$

$$p_{ss} = \begin{cases} \frac{n_{ch}}{n_s}, & n_s > n_{ch} \\ 1, & 1 \leq n_s \leq n_{ch} \\ 0, & n_s = 0 \end{cases} \tag{12}$$

Notations

N_s: num. of suc RR STAs

n_s: num. of suc contending STAs

n_{ch}: num. of channels

p_s: prob. of suc RR

p_{sc}: prob. of suc contending

p_{ss}: prob. of being selected

Resource Request (RR) are divided into two stages, one for random contending, another for AP selection.

If $n_s > n_{ch}$, which means not enough resource for request, AP will select n_{ch} STAs.

Compute p_{sc} and n_s

$$n_c(t) = n_c(t-1) - N_s(t-1) + \lambda', \quad (13)$$

$$\lambda' \sim \mathrm{B}(\mathbb{N}, \mathbb{P}),$$

$$\mathbb{N} = n - n_c(t-1) + N_s(t-1),$$

$$\mathbb{P} = 1 - e^{-\lambda T}$$

$$p_{sc} = \left(\frac{c_w - 1}{c_w}\right)^{n_c(t)-1} \quad (14)$$

Notations

λ': new arrival STAs for this TF-R period

n: num. of all STAs

n_c: num. of contending STA

n_s: num. of suc contending STAs

n_{ch}: num. of channels

N_s: num. of suc RR STAs

c_w: contending window size

p_{sc}: prob. of suc contending

$$P\{n_s = k\} = \sum_{j=k}^{n_c} (-1)^{k+j} \binom{j}{k} S_j, \ 1 \le k \le \min\{n_c, c_w\} \quad (15)$$

$$S_j = \binom{c_w}{j} \prod_{i=1}^{k} \binom{n_c - i + 1}{1} \frac{1}{c_w - i + 1} \left(1 - \frac{1}{c_w - i + 1}\right)^{n_c - i}$$

Above is the case when $n_c < c_w$. More derivation see appendix.

Expected value

$$E[p_t] = 1 - e^{-\lambda T} \tag{16}$$

$$E[n_c] = \lceil \frac{(1 - e^{-\lambda T})n}{1 - (1 - p_s)e^{-\lambda T}} \rceil \tag{17}$$

$$\approx \lceil (1 - e^{-\lambda T})n \rceil \tag{18}$$

$$E[p_{sc}] = (\frac{c_w - 1}{c_w})^{E[n_c]-1} \tag{19}$$

When traffic load is very light, λ is small, we need take ceiling of $E[n_c]$ to avoid $E[p_{sc}] > 1$. This approach only reduces the power efficiency.

$$E[p_{ss}] = \sum_{k=1}^{n_{ch}} P\{n_s = k\} + \sum_{k=n_{ch}+1}^{n_c} \frac{n_{ch}}{k} P\{n_s = k\} \tag{20}$$

Then probability of success RR is

$$E[p_s] = E[p_{sc}]E[p_{ss}] \tag{21}$$

Expected value

With distribution of n_s and definition of N_s (Equation 10), we have

$$E[N_s] = \sum_{k=1}^{n_{ch}} kP\{n_s = k\} + P\{n_s > n_{ch}\}n_{ch} \tag{22}$$

Then recall Equation 9 of R

$$E[R] = n_{ch}/E[N_s] \tag{23}$$

Now, we have $\triangle_{TX}$ and $\triangle_{RX}$, see Equation 4 and 5, so as to $\triangle_{idle}$ and $\triangle_{doze}$. At last substitute into Equation 1 to obtain the energy consumption.

Numerical Results–System Setup

The time scale is based on μs. T_p is the duration for transmitting a packet under normalized data rate.

Our model assumes a random access procedure with constant window size 32. It is a big assumption.

For power consumption, I assume P_{TX} is independent of the bandwidth. And I also ignore the inter-frame spacing (IFS) and contending procedure of TF.

Table 1: System Parameter Setting for Analysis

T_b	50 μs
T_p	500 μs
n_{ch}	10
c_w	32
P_{TX}	1000 mW
P_{RX}	600 mW
P_{idle}	300 mW
P_{doze}	150 mW

All above assumptions or simplifications are based on the first glimpse of the model and the system, figuring out the key factors and unexpected problems of some mechanism.

Numerical Results–Power Save Performance

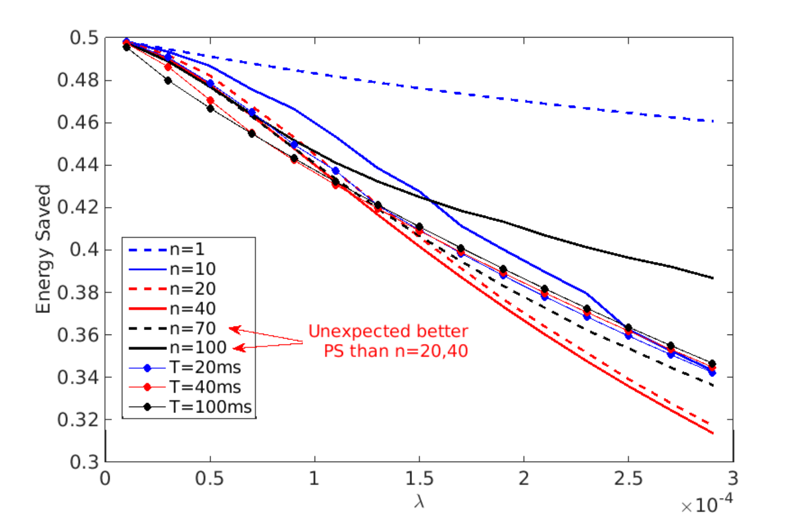
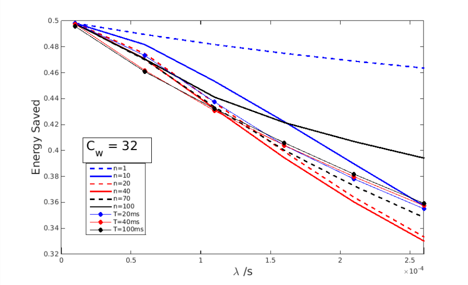


Figure 7: Power Save Performance with Different Parameters

Numerical Results–Power Save Performance

We find most results are as we thought.

- It's intuitive that as λ increasing, energy efficiency reduces, because our the effective transmission increase, the remaining waste energy are less.
- Period T is not important for energy saving, but should affect latency a lot.
- Intuitively, as n increases (more dense), PS will degrade. However, in our simulation, it's not always right.



Numerical Results–n_s behavior

n_{s1} is derivated using the distribution of n_s, and n_{s2} is derivated using equation 24. It validates the distribution of n_s.

Again, an unexpected phenomenon is as $n > 35$, n_s and N_s both decrease. It is because contention window c_w is small for more STAs.

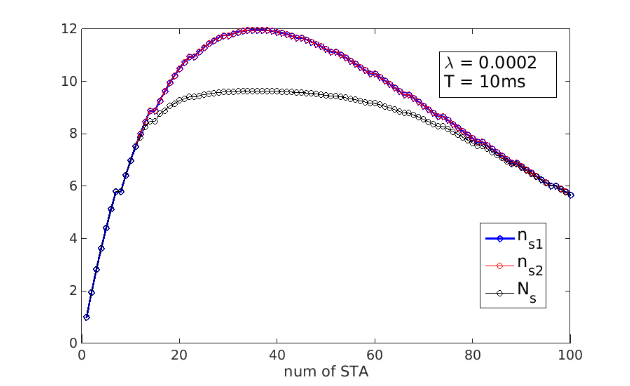


Figure 8: Success Contending STAs and Success RR STAs

Numerical Results–p_{sc}, p_{ss}, p_s

It is **expected** now that p_{ss} will increase after $n = 35$. Recalling equation 12, since N_s decrease after $n = 35$, p_{ss} increases.

Also, with N_s decreasing, R increase; with p_s increasing, both above help **power save**.

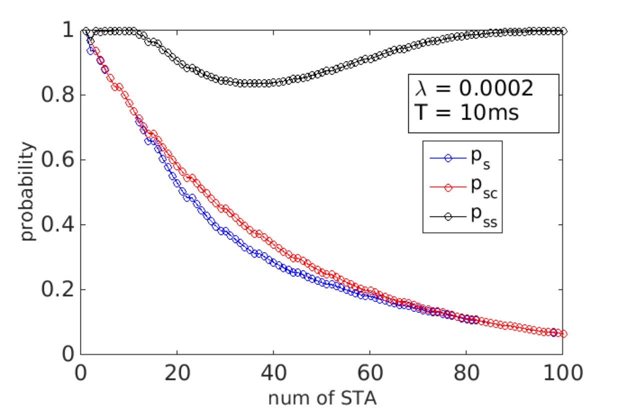


Figure 9: Probability of Success Contending (p_{sc}), Selecting (p_{ss}) and RR (p_{ps})

Numerical Results–PS with Modified c_w

We can see that larger c_w will make the result as we thought intuitively that the more STAs, the power save is more serious. The unexpected phenomenon comes from our big assumption "random access for RR with constant $c_w = 32$".

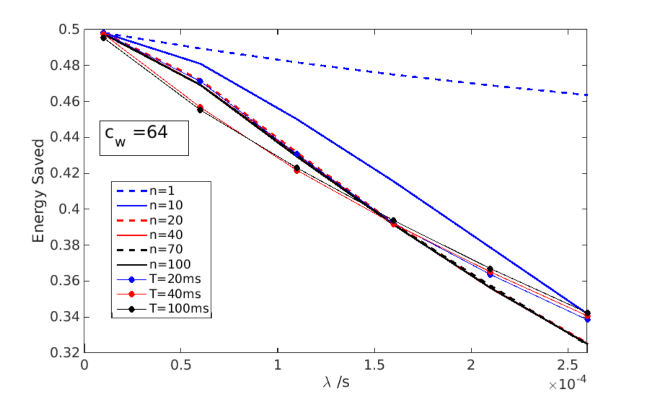


Figure 10: Power Save Performance with $c_w = 64$

Issues

Issues

What I did

- A power save design for 802.11ax UL.
- A model and numerical results help obtain the insight of the design.
- A discrete-time event simulation.

In progress idea and work

- A improved model to do Latency Analysis (queueing model)
- Dense Network: A scheduler to schedule UL/DL efficiently. The hardness is that UL traffic is unknown.
- Learn how to predict UL traffic. Predict according to last TF period.

Think more

- What if unexpected interference?

Appendix

Distribution of n_s

The number of successful contending STAs in random access equals to a problem as follows.

Given n buckets, and m balls, put the balls randomly into the buckets.

We want to know the distribution of number of buckets which contain only one ball. Let X be the number of such buckets. Y_i denotes number of balls in bucket i. Then

$$X = \sum_{i=1}^{n} \mathbb{1}_{Y_i=1}$$

A_i: event that bucket i contains only one ball.

To begin, for $1 \leq k \leq m$, let

$$S_k = \sum_{i_i < \ldots < i_k} P(A_{i_1} \ldots A_{i_k})$$

equal the sum of the probabilities of all the $\binom{n}{k}$ intersections of k distinct events.

Distribution of n_s

With above formulation, the distribution of X is given as follows. [6, p.74-76]

$$P\{X = k\} = \sum_{j=k}^{n} (-1)^{k+j} \binom{j}{k} S_j$$

$$= S_k - \binom{k+1}{k} S_{k+1} + \cdots + (-1)^{n-k} \binom{n}{k} S_n$$

$$S_j = \binom{n}{j} \prod_{i=0}^{j-1} \binom{m-i}{1} \frac{1}{n-i} (1 - \frac{1}{n-i})^{m-i-1}$$

The expected value is easy to compute.

$$E[X] = E[\sum_{i=1}^{n} \mathbb{1}_{Y_i=1}] = \sum_{i=1}^{n} E[\mathbb{1}_{Y_i=1}] = \sum_{i=1}^{n} \binom{m}{1} \frac{1}{n} (1 - \frac{1}{n})^{m-1} \tag{24}$$

References I

UI mu procedure.
2015-03-09.

Identifiers in he ppdus for power saving.
2015-09-12.

Power save with random access.
2015-09-14.

G. Bianchi.
Performance analysis of the ieee 802.11 distributed coordination function.
Selected Areas in Communications, IEEE Journal on, 18(3):535–547, 2000.

References II

E.-Y. Lin.
A comprehensive study of power-efficient rendezvous schemes for wireless sensor networks.
2005.

S. M. Ross.
Introduction to probability models.
Academic press, 2014.

W. Ye, J. Heidemann, and D. Estrin.
An energy-efficient mac protocol for wireless sensor networks.
In *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, volume 3, pages 1567–1576. IEEE, 2002.

Thanks