Power Efficiency and Delay Tradeoff of Energy Efficient Ethernet Protocol

Xiaodan Pan, Tong Ye, Tony T. Lee, Weisheng Hu
pxd0506@sjtu.edu.cn

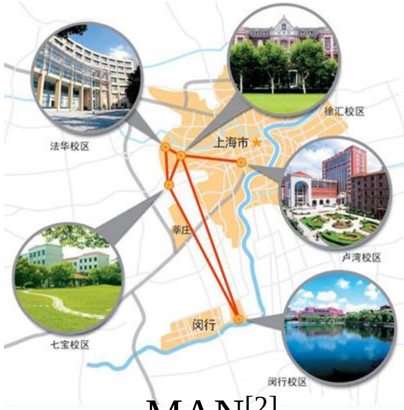
State Key Lab of Advanced Optical Communications and Networks
Shanghai Jiao Tong University

Outline

- Background
- Energy Efficient Ethernet Protocol
- Vacation Model
- Power Efficiency
- P-K Formula of Mean Delay
- Tradeoff and Parameter Selections
- Conclusion

Widely Applied Ethernets

Data Center[1]



MAN[2]

LAN

WAN[3]

[1] A. Greenberg, J.R. Hamilton, N. Jain, et al, "VL2: a scalable and flexible data center network," *Proc. ACM SIGCOMM*, 2009, pp. 51-62.
[2] M. Huynh, P. Mohapatra, "Metropolitan Ethernet Network: A move from LAN to MAN," *Computer Networks*, vol. 51, pp. 4867-4894, Dec 2007.
[3] A. Kasim, P. Adhikari, N. Chen, et al, "Ethernet: From LAN to the WAN," in *Delivering Carrier Ethernet*, 1st ed., New York: McGraw-Hill, 2007, pp.3-43.

Growing of Ethernet Devices

- The number of devices is huge and still grows rapidly.

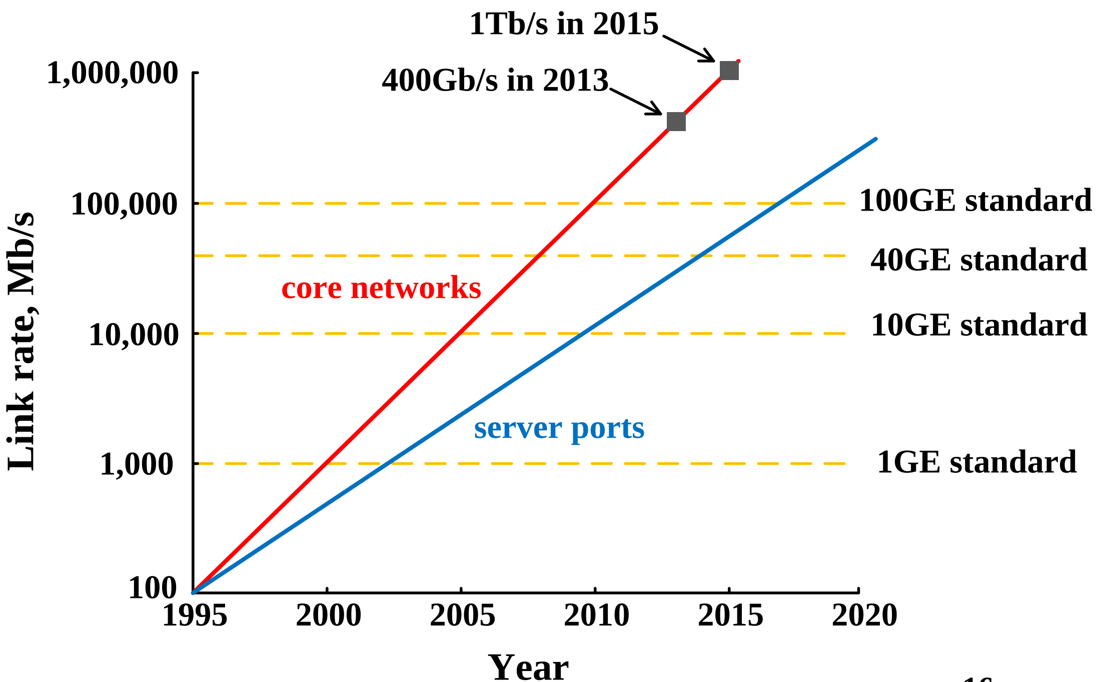
Unit: Billion RMB

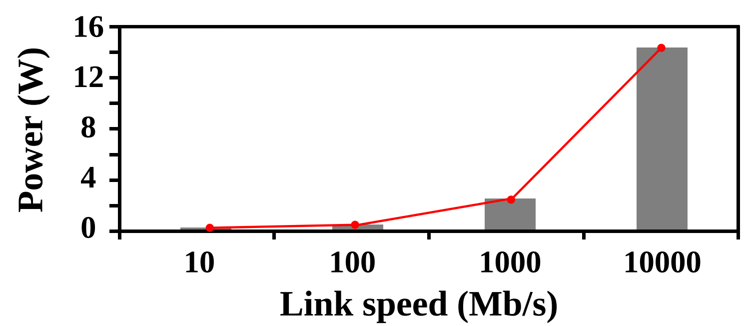
Datas Source: CCW Research 2014/04

Network Equipment Market Scale and Forecast of China

[1] http://www.ccwresearch.com.cn/view_point_detail.htm?id=557063
[2] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future Internet: A survey of existing approaches and trends in energyaware fixed network infrastructures," *IEEE Communications Surveys Tutorials*, vol. 13, pp. 223–244, Second 2011.

Increase of Data Rate

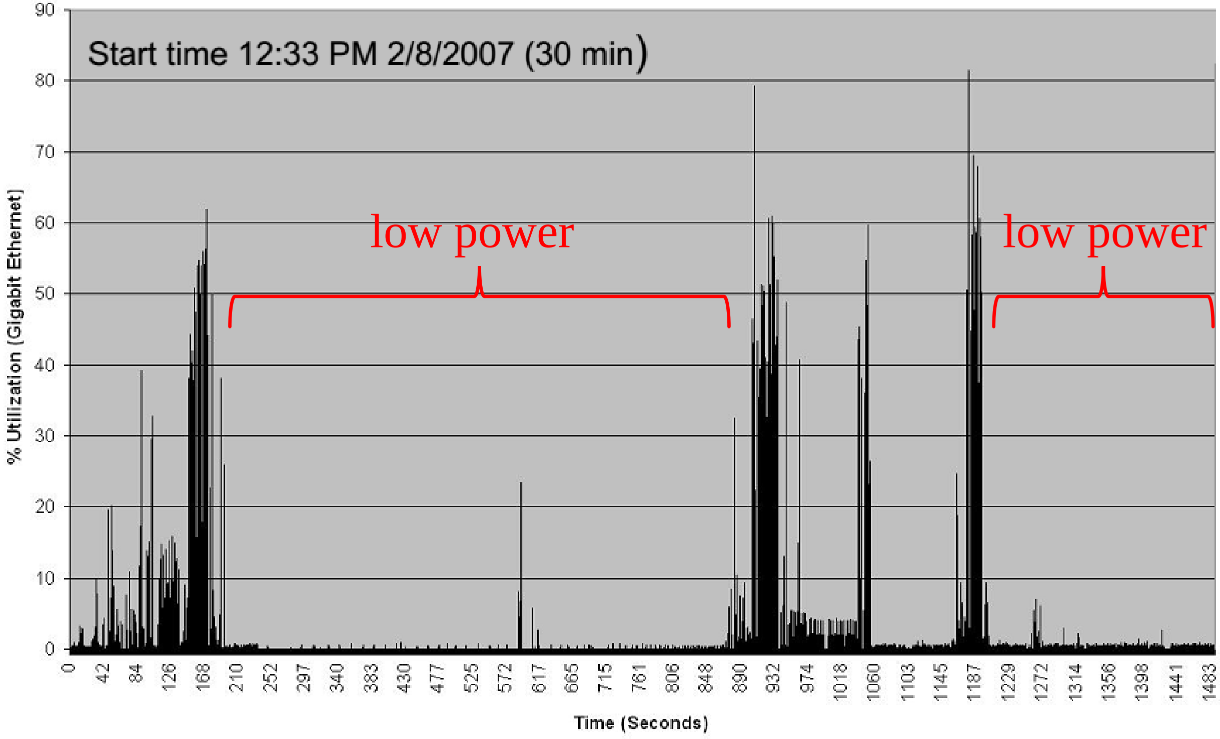




[1] P. J. Winzer, "Beyond 100G Ethernet," *IEEE Communications Magazine*, vol. 48, pp. 26–30, July 2010.
[2] P. Reviriego, K. Christensen, J. Rabanillo, and J. A. Maestro, "An initial evaluation of Energy Efficient Ethernet," *IEEE Communications Letters*, vol. 15, pp. 578–580, May 2011.
[3] B. Kohl, "10GBASE-T power budget summary," 2007.

Idea of Energy Saving

- IEEE 802.3az: Shut down some component during idle periods and make the system more energy proportional to load



Trace from LBNL: File Server with 1G Ethernet Link

[1] H. barrass, C. M. Bennett, B. Nordman, "Energy Efficient Ethernet," IEEE Tutorial, Jul 2007

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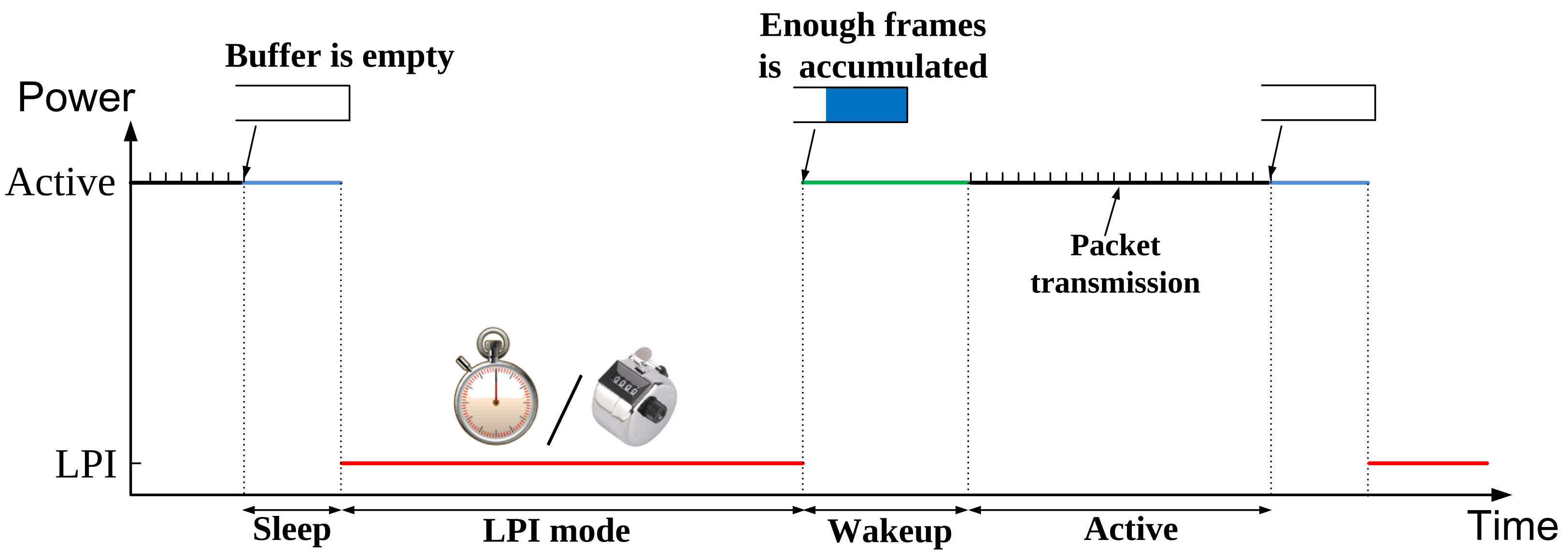
Energy Efficiency Ethernet Protocol

- Sleep: transition time from Active to LPI
- Wakeup: transition time from LPI to Active
- LPI: low power idle mode
- Active: packets transmission period



A Typical State Transition and Power Consumption of EEE Protocol

Counter and Timer

- Counter N
  - Bound the backlogged queue length
- Timer τ ($\tau > T_s$)
  - Bound the delay

τ&N policy

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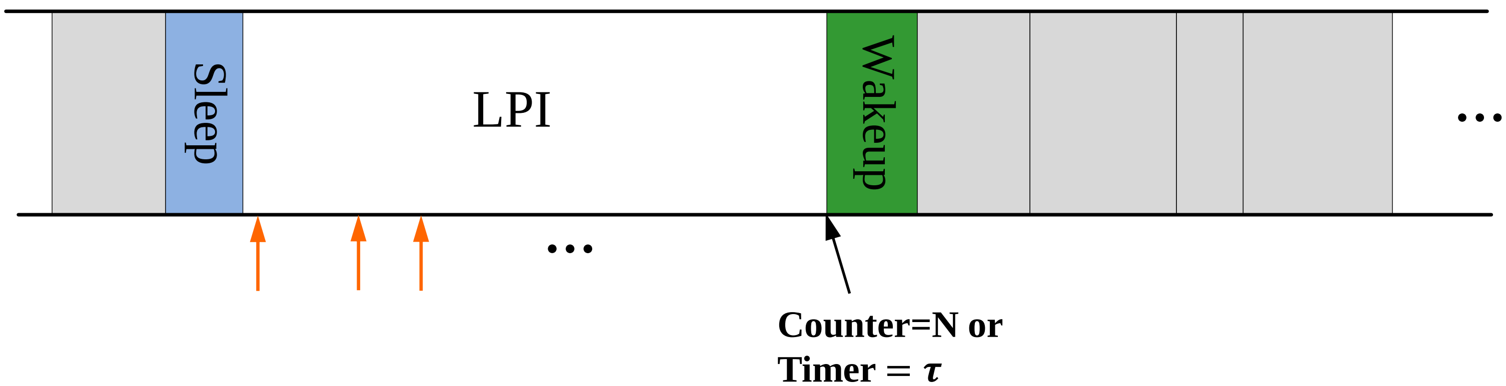

τ&N policy

Counter and Timer

- Counter N
  - Bound the backlogged queue length
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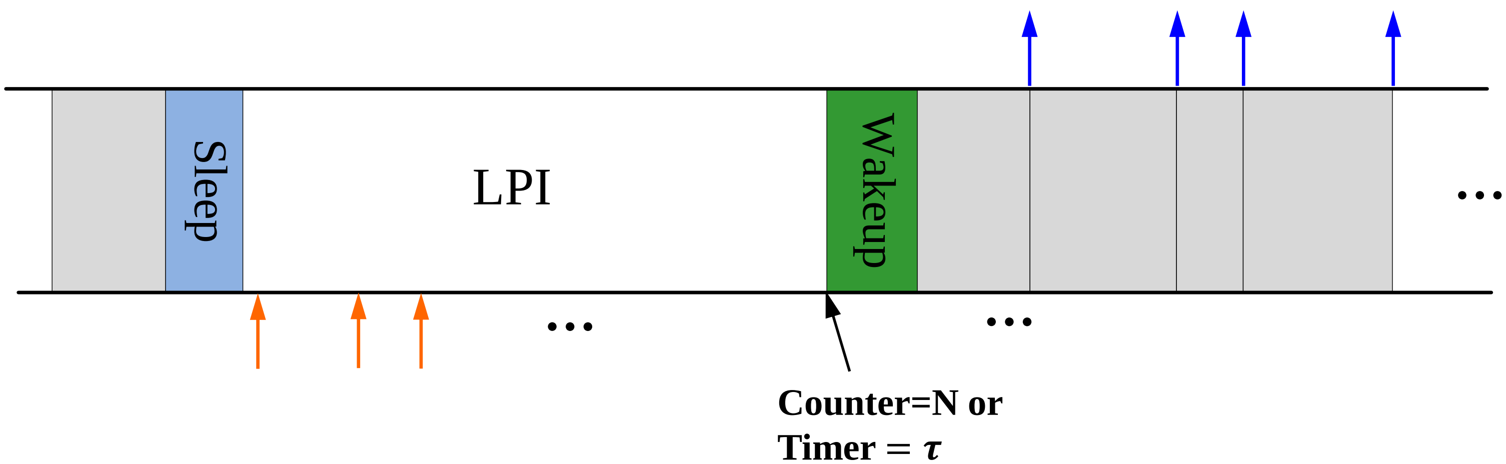
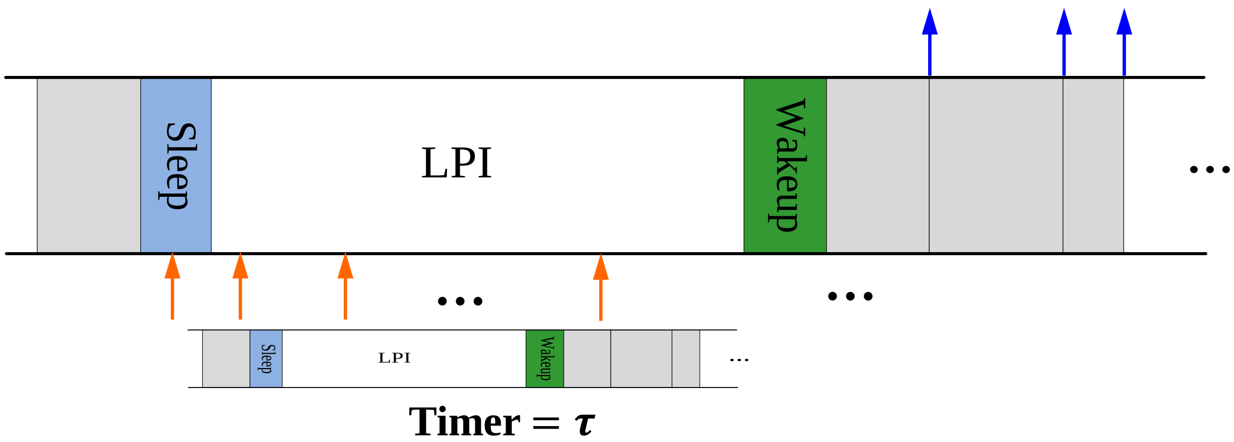


τ&N policy

τ policy and N policy

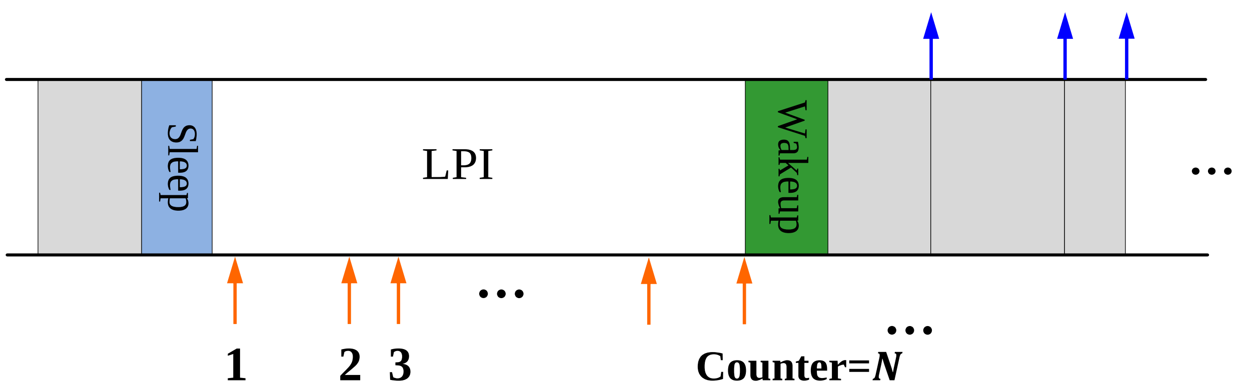
τ policy

$N \to \infty$



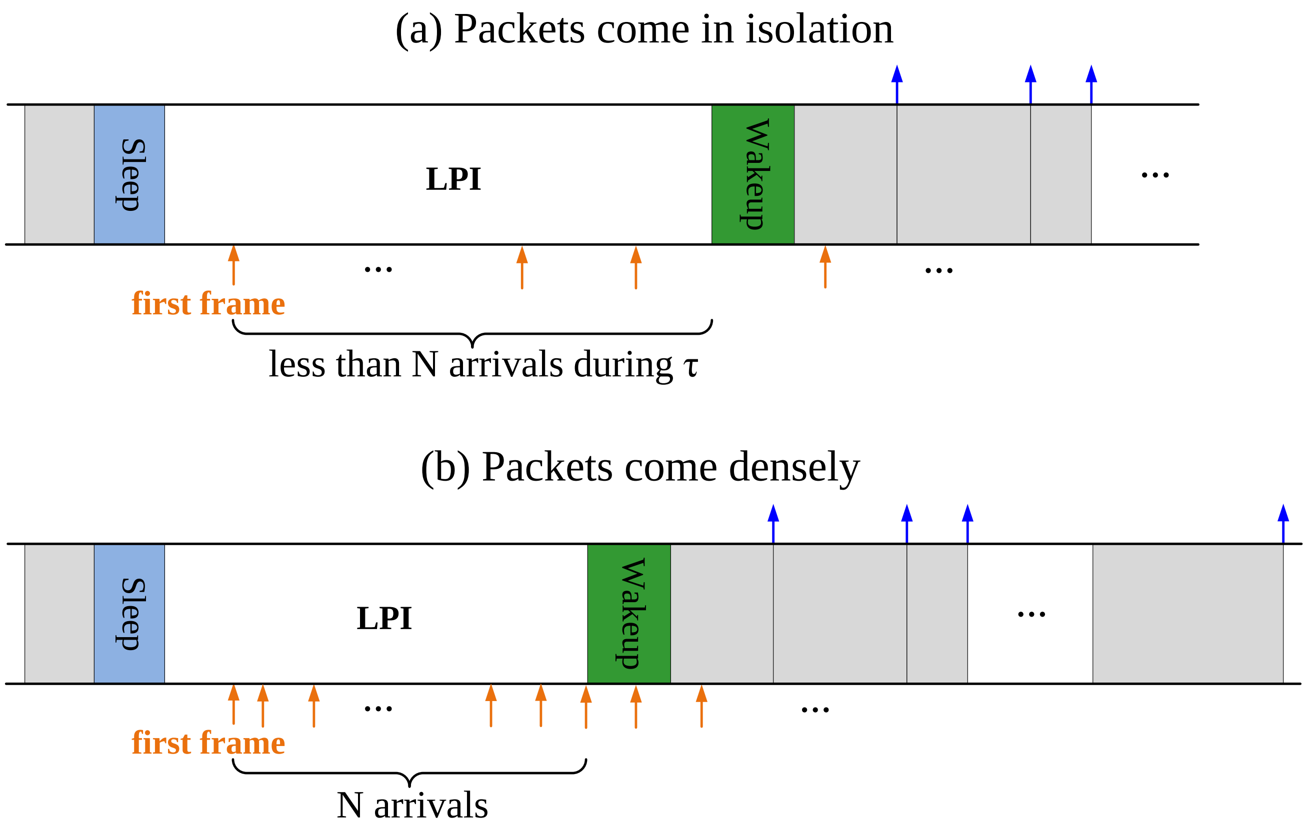
N policy

$\tau \to \infty$



Performance Tradeoff

- Power efficiency is improved at the expanse of delay.
- How to select N and τ to optimize system performances?



Our Works

- Model BTR strategy as an M/G/1 queue with vacation time which is governed by the arrival process.
- Derive the P-K formula of mean delay.
- Demonstrate the impacts of counter and timer on performances and provide two rules to select appropriate parameters N and τ.

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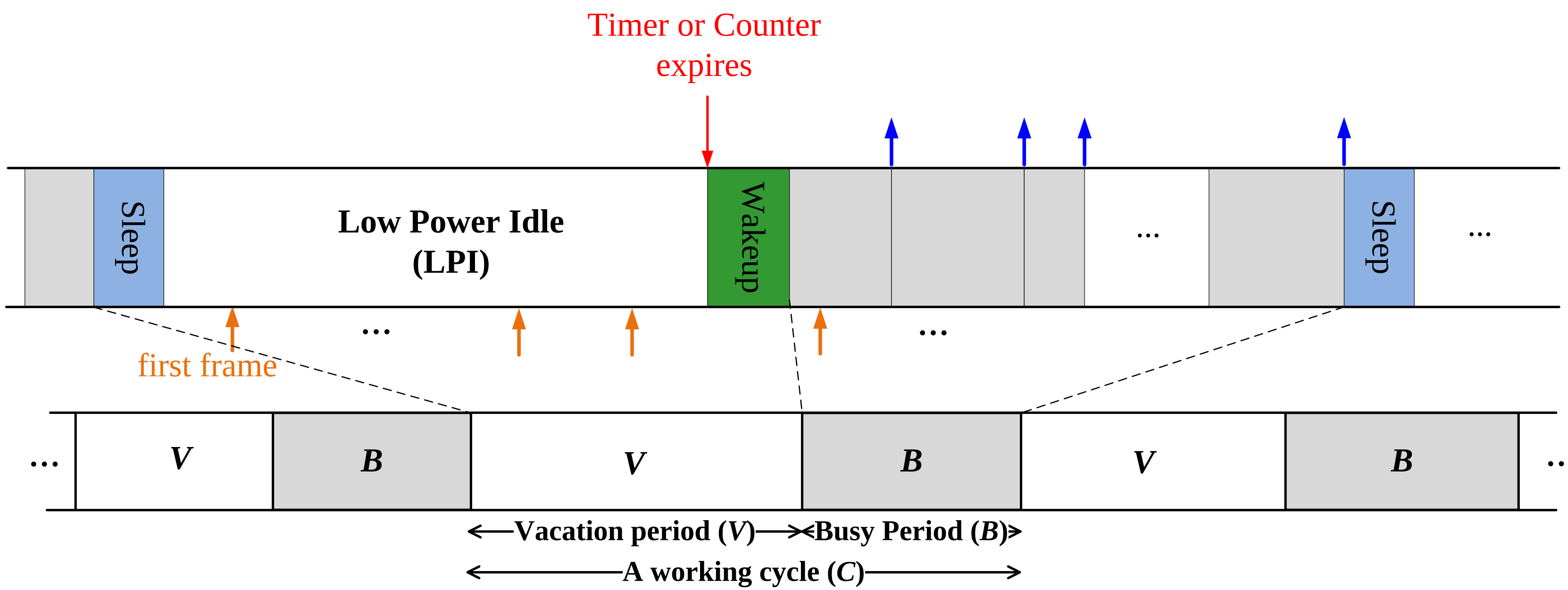
Cycles of EEE Working Process

- A renewal cycle (C)=Vacation period(V)+Busy period(B)



EEE Working Process

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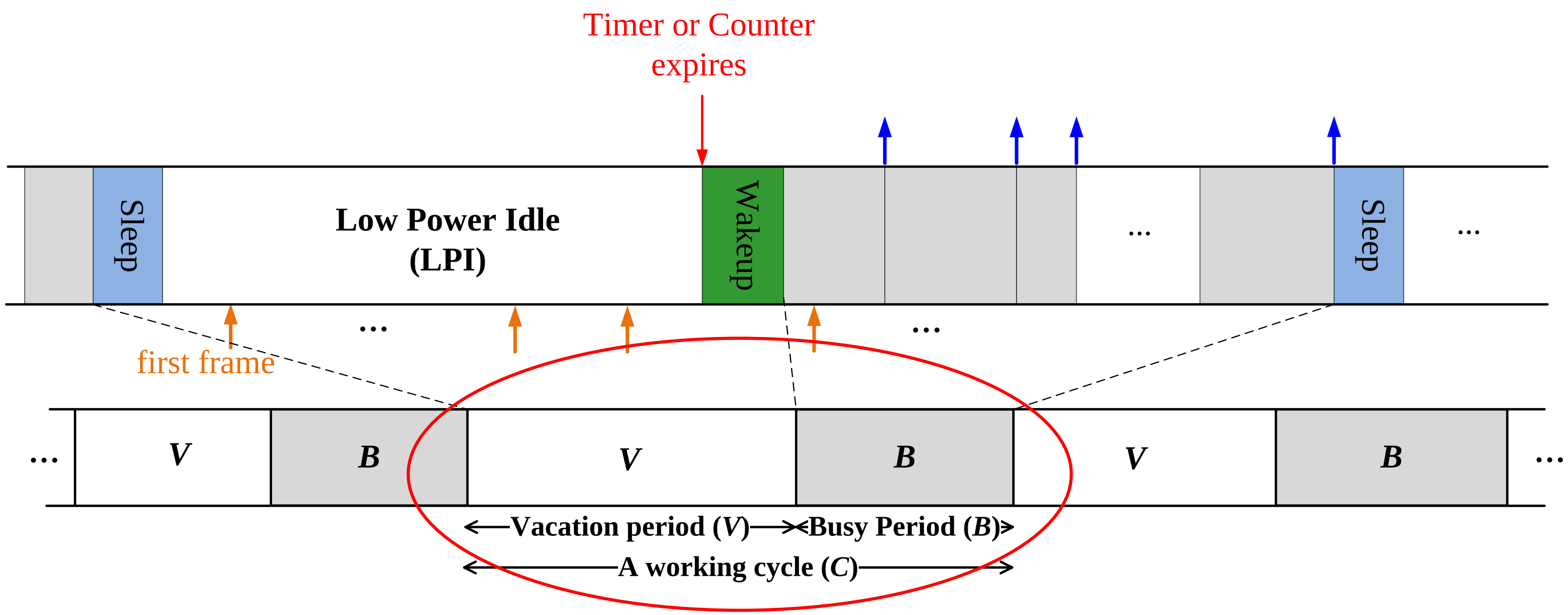
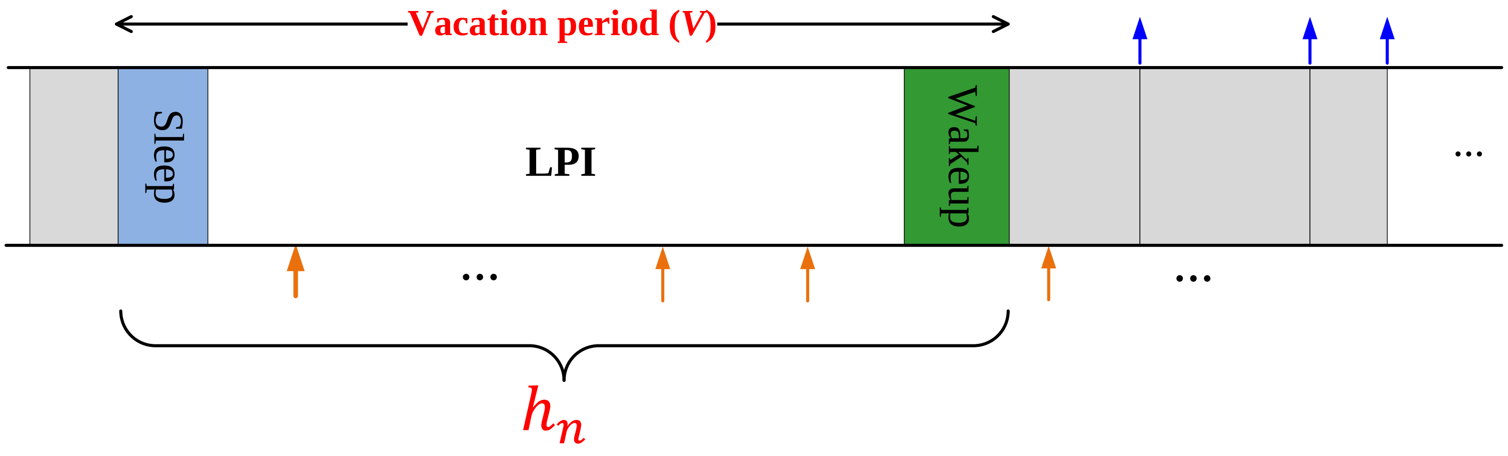


EEE Working Process

Key to Model the EEE Protocol

- Vacation period depends on the probability h_n

$$h_n = Pr\{n\ arrivals\ during\ a\ vacation\ period\ V\}$$



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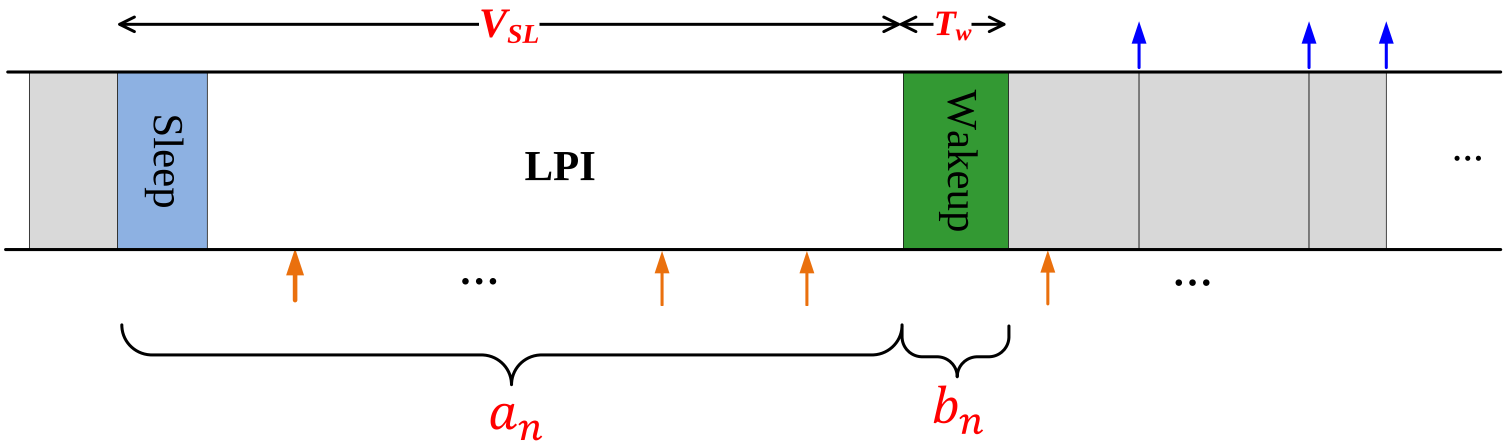
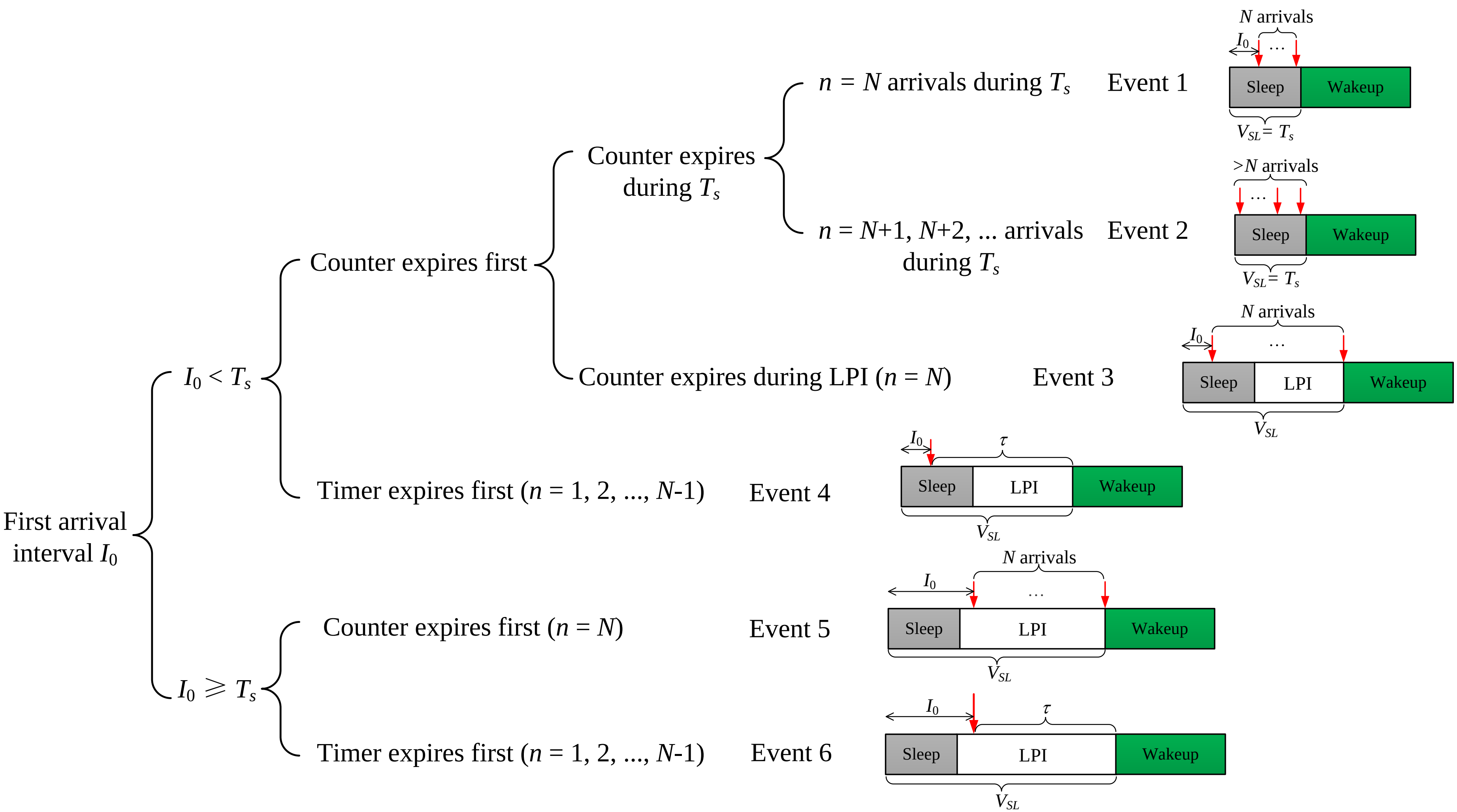


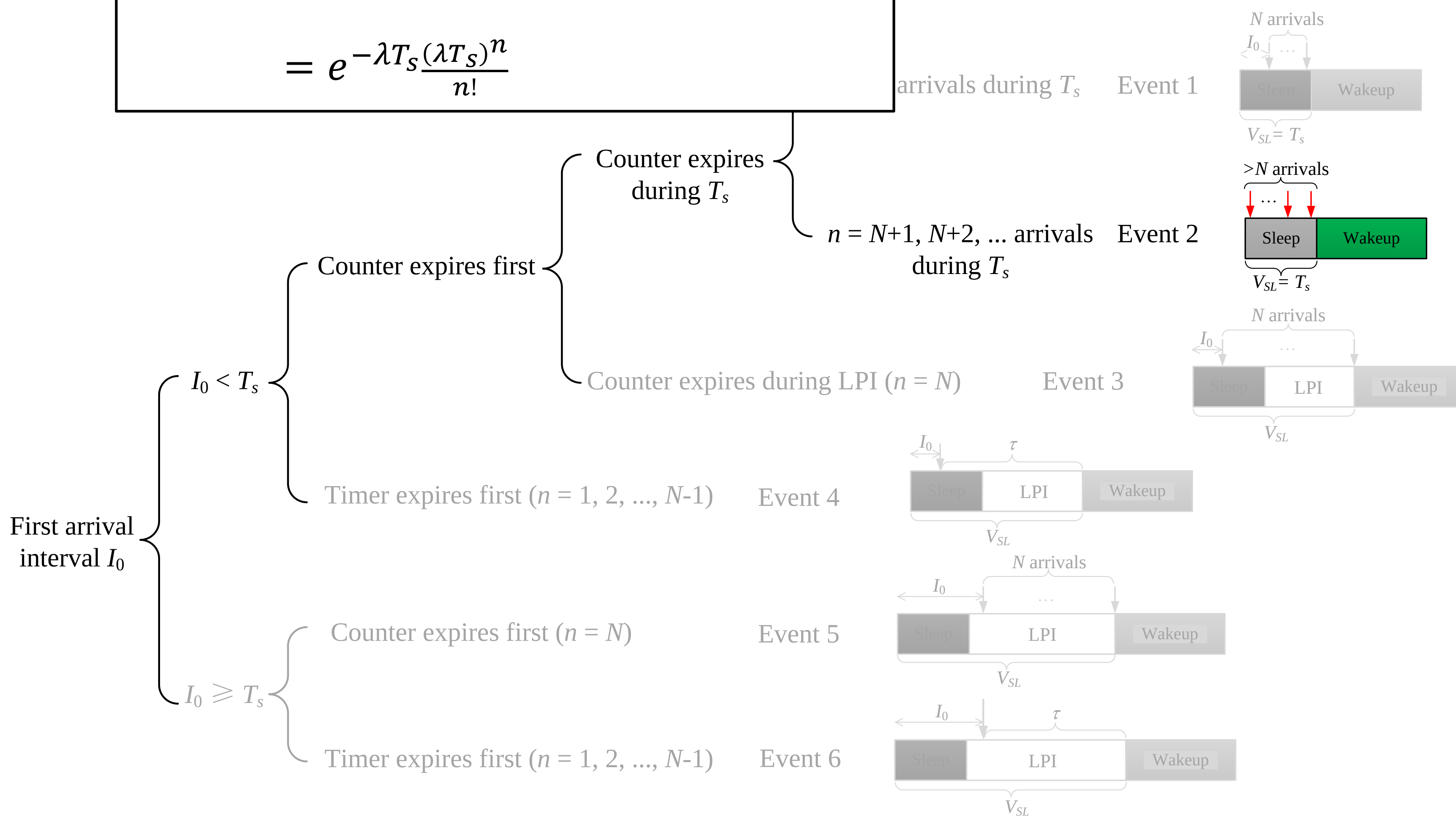
Arrival Event Tree of Vacation Period

- Six mutually independent events



$a_n\ (n > N)$

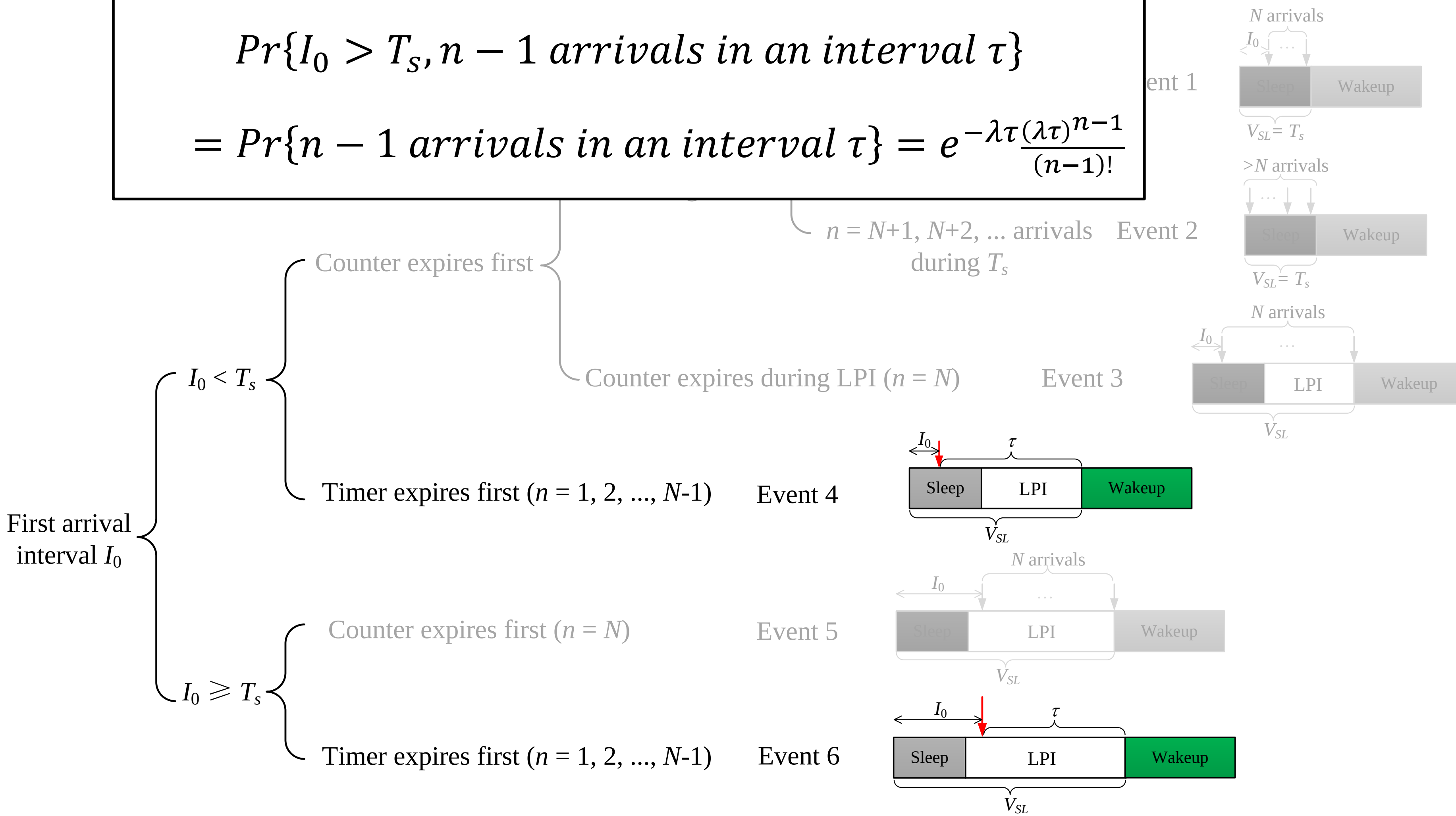
$$a_n = Pr\{n \text{ arrivals in the interval } T_s\}$$
$$= e^{-\lambda T_s}\frac{(\lambda T_s)^n}{n!}$$



$a_n \ (0 < n < N)$

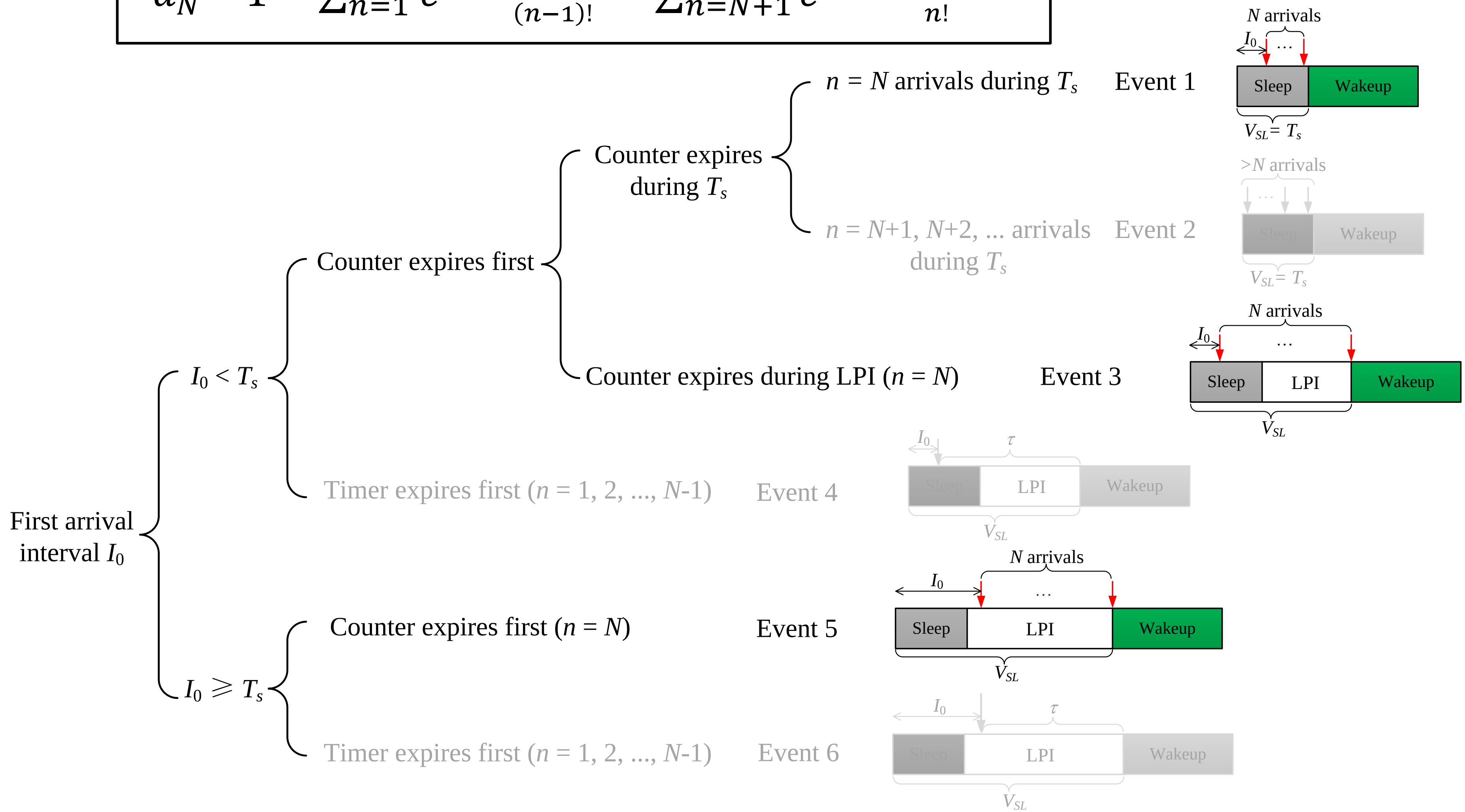
$$a_n = Pr\{I_0 \le T_s, n-1 \ arrivals \ in \ an \ interval \ \tau\} + Pr\{I_0 > T_s, n-1 \ arrivals \ in \ an \ interval \ \tau\}$$

$$= Pr\{n-1 \ arrivals \ in \ an \ interval \ \tau\} = e^{-\lambda\tau}\frac{(\lambda\tau)^{n-1}}{(n-1)!}$$



$a_n \ (n = N)$

$$a_N = 1 - \sum_{n=1}^{N-1} e^{-\lambda\tau}\frac{(\lambda\tau)^{n-1}}{(n-1)!} - \sum_{n=N+1}^{\infty} e^{-\lambda T_s}\frac{(\lambda T_s)^{n}}{n!}$$



Probability h_n

$$a_n = \begin{cases} 0, & n = 0 \\ e^{-\lambda\tau}\frac{(\lambda\tau)^{n-1}}{(n-1)!}, & n = 1,2,\cdots,N-1 \\ \sum_{n=0}^{N} e^{-\lambda T_S}\frac{(\lambda T_S)^n}{n!} - \sum_{n=1}^{N-1} e^{-\lambda\tau}\frac{(\lambda\tau)^{n-1}}{(n-1)!}, & n = N \\ e^{-\lambda T_S}\frac{(\lambda T_S)^n}{n!}, & n = N+1, N+2, \cdots \end{cases}$$

$$b_n = Pr\{n\ arrivals\ during\ T_w\} = e^{-\lambda T_W}\frac{(\lambda T_W)^n}{n!}$$

$$\rightarrow h_n = \sum_{k=0}^{n} a_{n-k}\, b_k \rightarrow H(z) = A(z)B(z)$$

Mean Vacation Time

- Mean number of arrivals during vacation is

$$\bar{\alpha} = H'(1)$$

  - $H(z) = \sum_{n=0}^{\infty} h_n z^n$
  - $\bar{\alpha}$: mean number of arrivals during vacation period

- By Little's Law, the mean vacation time $\bar{V}$ is

$$\bar{\alpha} = \lambda \bar{V} \rightarrow \bar{V} = \frac{\bar{\alpha}}{\lambda}$$

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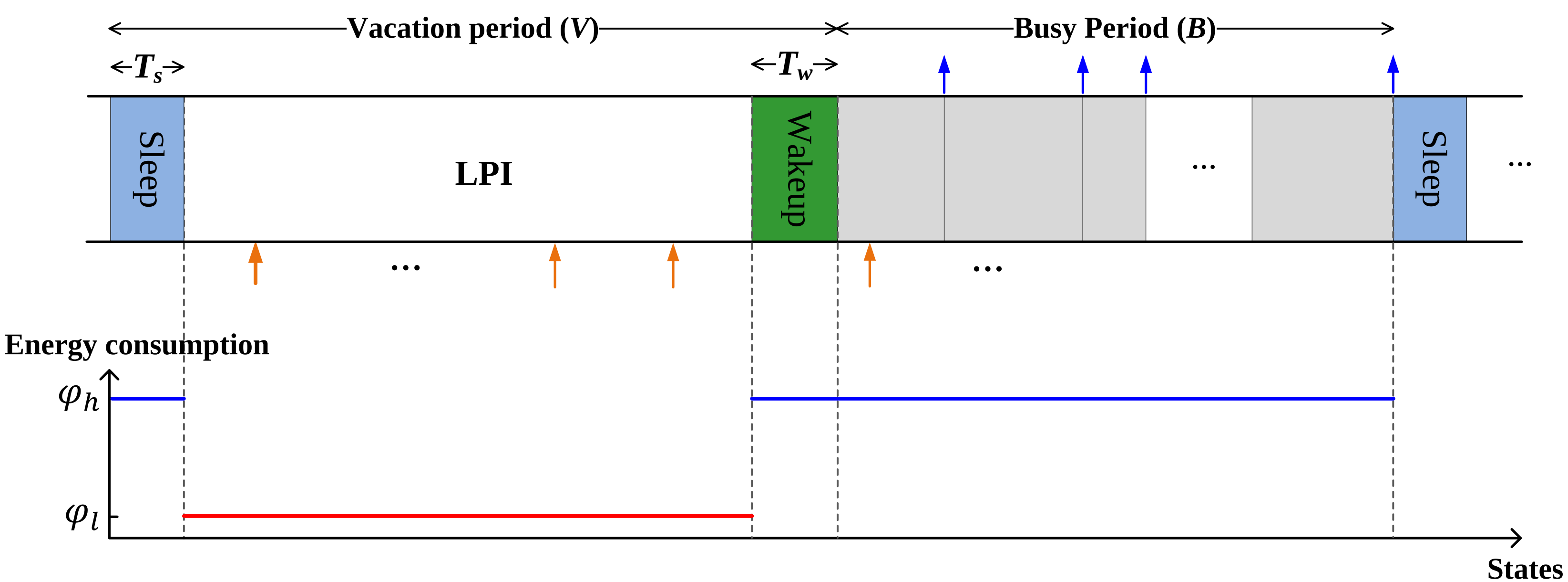
Power Efficiency η

$$\eta = \frac{\varphi_h - \varphi_{EEE}}{\varphi_h} = \left(1 - \frac{T_w + T_s}{\overline{V}}\right) \cdot \frac{(1-\rho)\times(\varphi_h - \varphi_l)}{\varphi_h}$$

When N and τ come to infinite

$$\eta^* = \lim_{\overline{V}\to\infty} \eta = \frac{(1-\rho)\times(\varphi_h - \varphi_l)}{\varphi_h}$$



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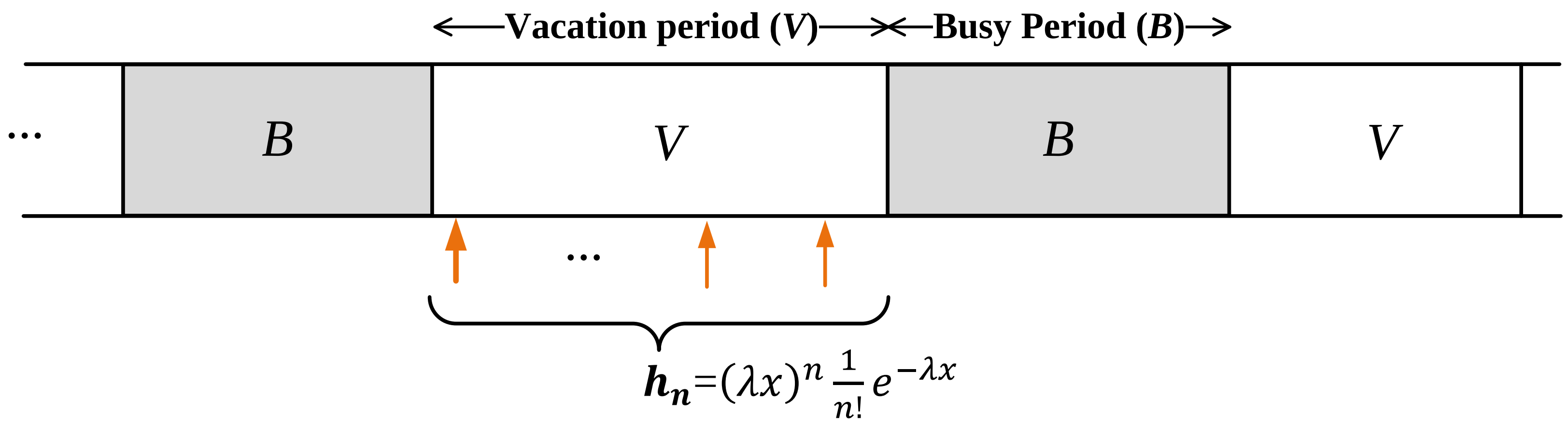
Classical M/G/1 with Vacation System

- Vacation time distribution is independent of the arrival process

$$H(z) = \sum_{n=0}^{\infty} h_n z^n = \sum_{n=0}^{\infty} \int_0^{\infty} (\lambda x)^n \frac{1}{n!} e^{-\lambda x} \, dV(x) z^n$$
$$= V^*(\lambda - \lambda z)$$



Classical M/G/1 with Vacation

Failure of $H(z) = V^*(\lambda - \lambda z)$

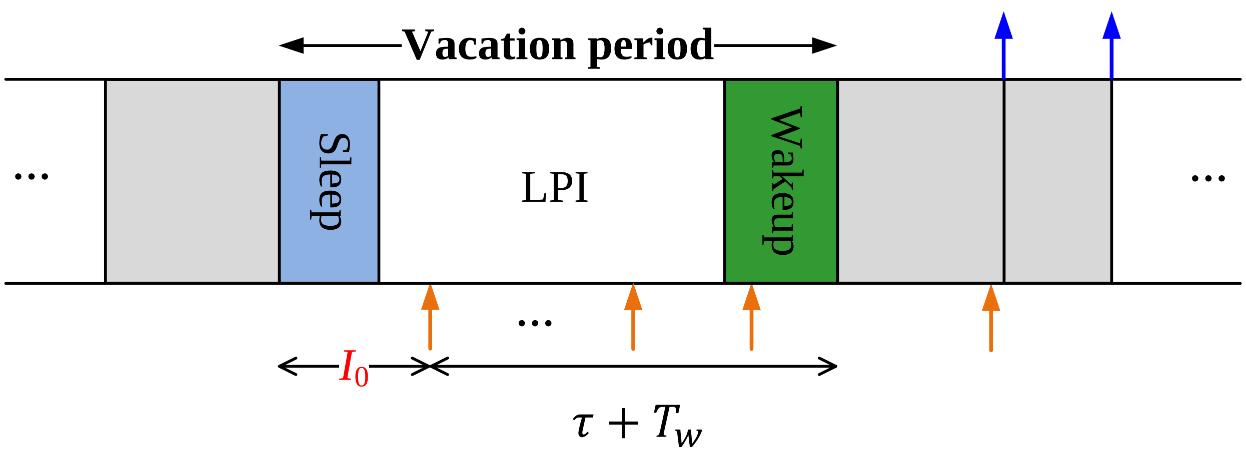
- In EEE protocol, the vacation time is completely governed by the arrival process. Take τ policy for example

$$V = I_0 + \tau + T_w$$

$$v(x) = \lambda e^{-\lambda(x-\tau-T_w)}(x \geq \tau + T_w) \rightarrow V^*(s) = \frac{\lambda}{\lambda+s} e^{-s(\tau+T_w)}$$

$$h_n = e^{-\lambda(\tau+T_w)} \frac{[\lambda(\tau+T_w)]^{n-1}}{(n-1)!} (n \geq 1) \rightarrow H(z) = z e^{-\lambda(1-z)(\tau+T_w)}$$

- Obviously, $H(z) \neq V^*(\lambda - \lambda z)$

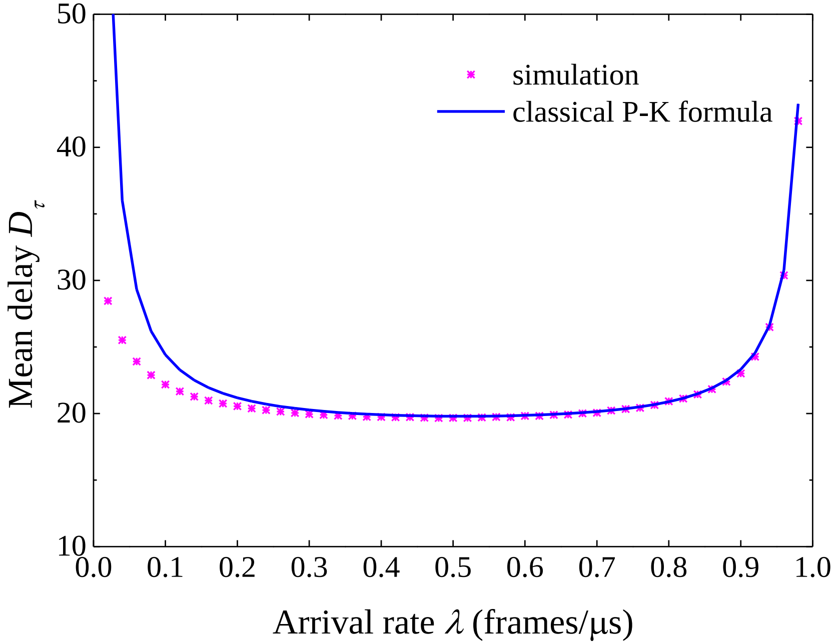


Failure of Traditional P-K Formula

- P-K Formula in the classical M/G/1 queue with vacation time

$$D = \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{\overline{V^2}}{2\overline{V}} + \bar{X}$$

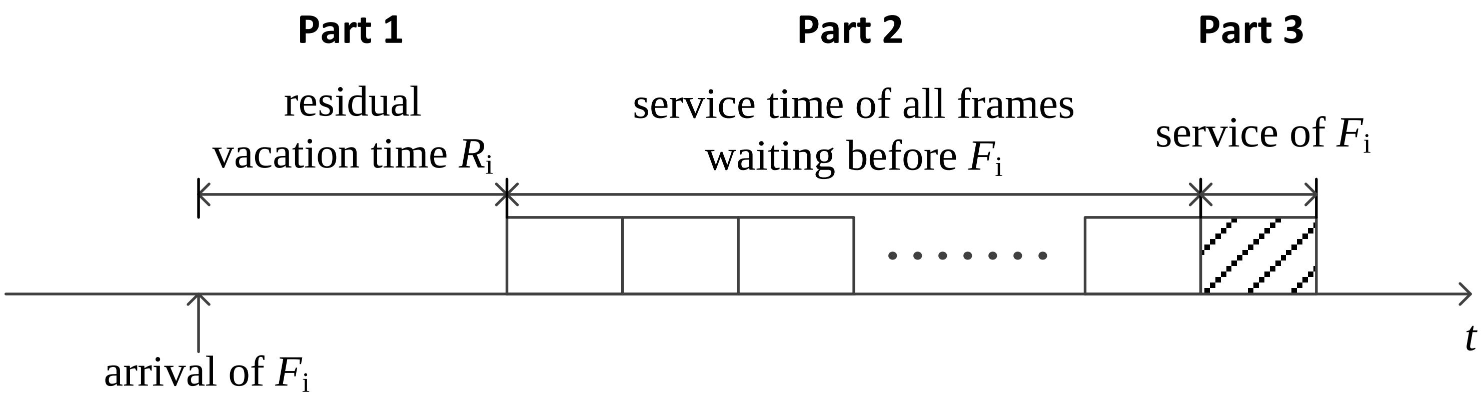
For the same reason, it fails in EEE systems



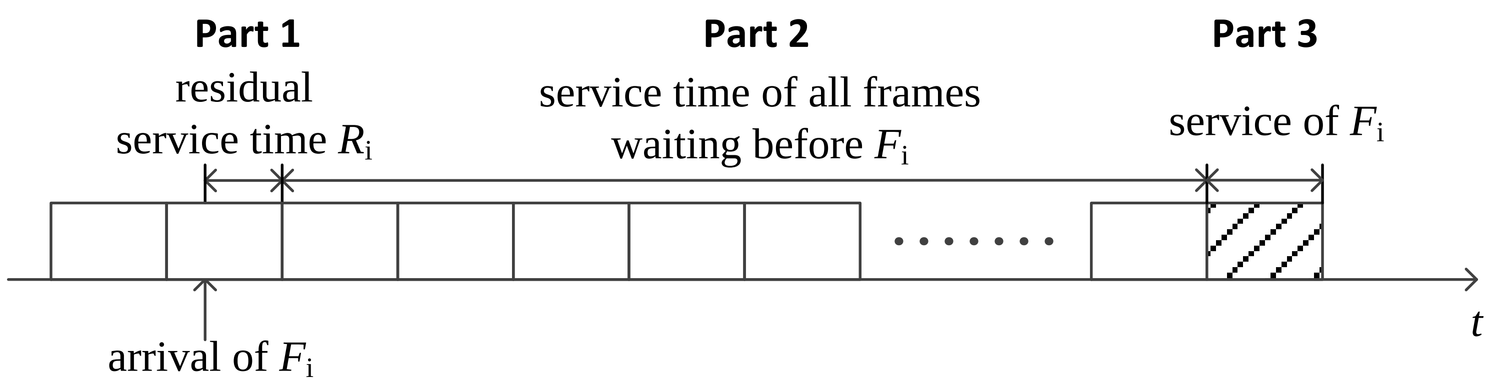
Validation of the Classical P-K Formula

Delay Analysis

- The waiting time for a frame is constituted by three parts.



(a) Frame F_i arrive during vacation period

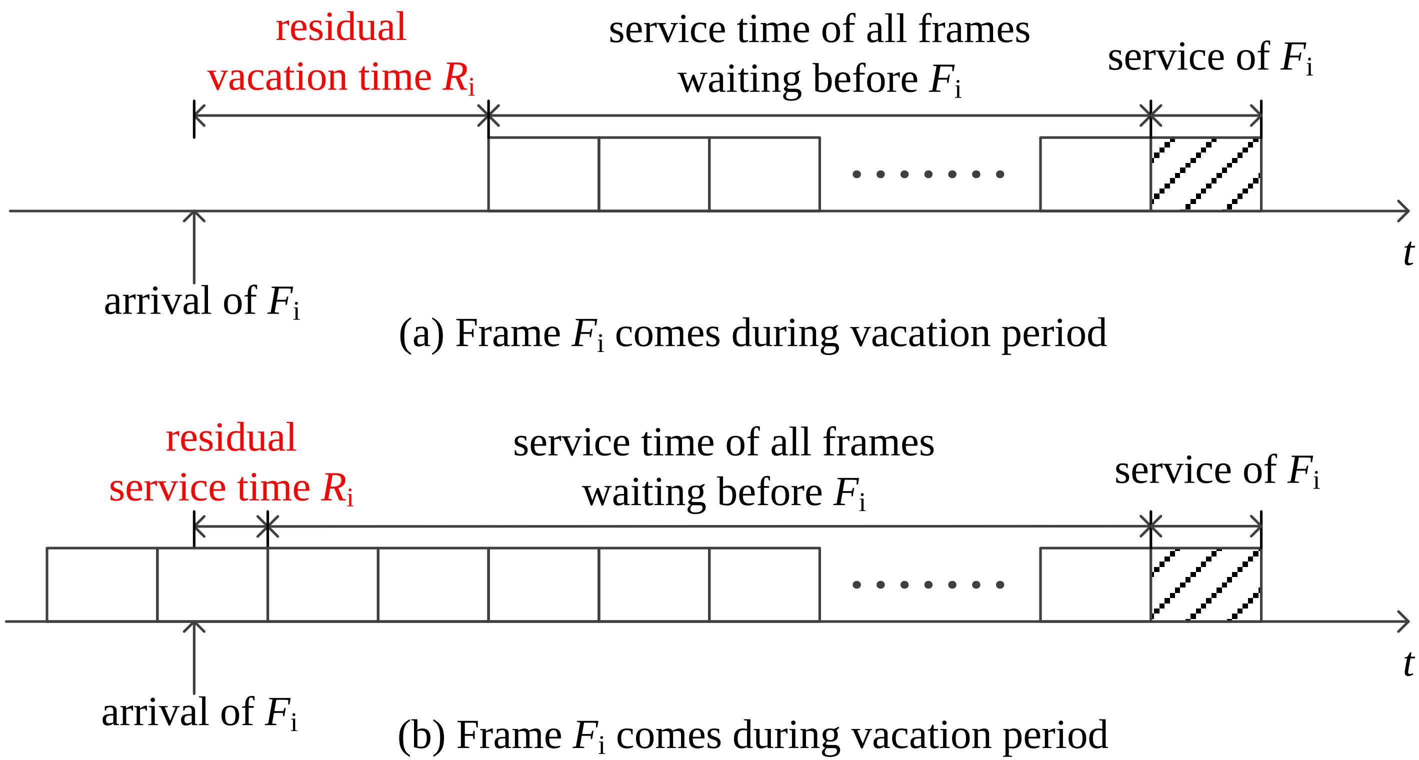


(b) Frame F_i arrive during busy period

Mean Delay

$$D = \frac{R}{1-\rho} + X$$

- R: mean residual time



(a) Frame F_i comes during vacation period

(b) Frame F_i comes during vacation period

[1] D. P. Bertsekas, R. G. Gallager, and P. Humblet, *Data networks*, vol. 2. Prentice-Hall International New Jersey, 1992.

Mean Residual Time

$$R = \boldsymbol{E}[\boldsymbol{R_i}|\boldsymbol{\xi} = \boldsymbol{0}] \times Pr\{\xi = 0\} + \boldsymbol{E}[\boldsymbol{R_i}|\boldsymbol{\xi} = \boldsymbol{1}] \times Pr\{\xi = 1\}$$

$$= E[R_i|\xi = 0] \times (1 - \rho) + E[R_i|\xi = 1] \times \rho$$

$$\xi = \begin{cases} 0, & \text{if a arrival comes during a vacation period} \\ 1, & \text{if a arrival comes during a busy period} \end{cases}$$

$$E[R_i|\xi = 1] = \frac{1}{2\rho}\lambda\overline{X^2}^{[1]}$$

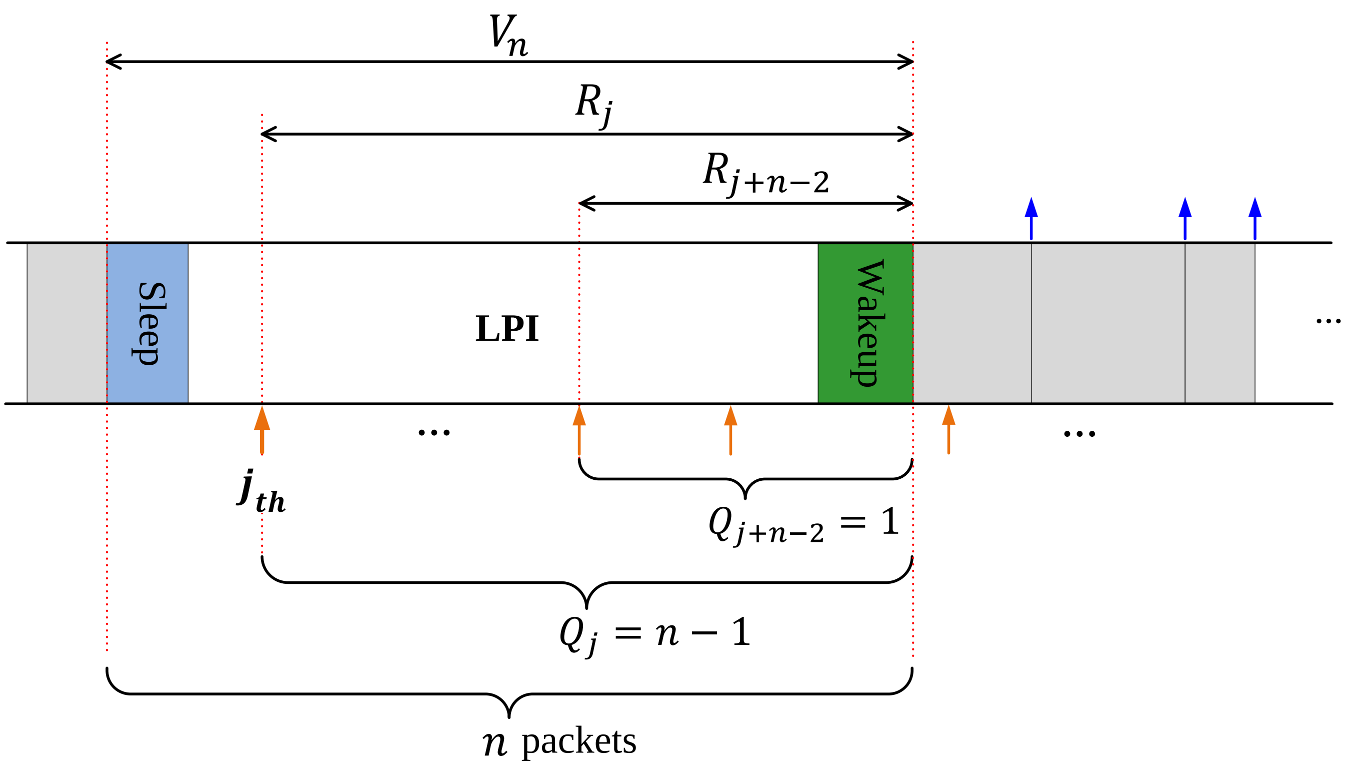
$$E[R_i|\xi = 0] = ?$$

[1] D. P. Bertsekas, R. G. Gallager, and P. Humblet, *Data networks*, vol. 2. Prentice-Hall International New Jersey, 1992.

Residual Vacation Time of Each Arrival

- When given V_n, # of arrival during the residual vacation time seen by a frame is determined.

V_n: vacation period terminated with n arrivals
Q_j: # of arrival during residual vacation time R_j



Mean Residual Vacation Time

$$E[R_i|\xi = 0] = \sum_{n=1}^{\infty} E[R_i|\xi = 0, frame\ i\ arrives\ in\ a\ V_n] \cdot P_n$$

- Applying Little's Law

$$\lambda E[R_i|\xi = 0] = \sum_{n=1}^{\infty} \lambda E[R_i|\xi = 0, frame\ i\ arrives\ in\ a\ \ V_n] \cdot P_n$$

$$= \sum_{n=1}^{\infty} E[Q_i|\xi = 0, frame\ i\ arrives\ \ V_n] \cdot P_n$$

$$= \sum_{n=1}^{\infty} \left[\frac{(n-1)+(n-2)+\cdots+1+0}{n}\right] \cdot \frac{n \cdot h_n}{H'(1)} = \frac{H''(1)}{2H'(1)}.$$

P-K Formula of Mean Delay

- **Theorem 1:** The mean delay of EEE systems is given by:

$$D = \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{H''(1)}{2\lambda H'(1)} + \bar{X}$$

- Classical P-K Formula

$$D = \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{\overline{V^2}}{2\bar{V}} + \bar{X}$$

  - When $H(z) = V^*(\lambda - \lambda z)$ holds, $D = \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{H''(1)}{2\lambda H'(1)} + \bar{X}$ degenerate into the classical form.

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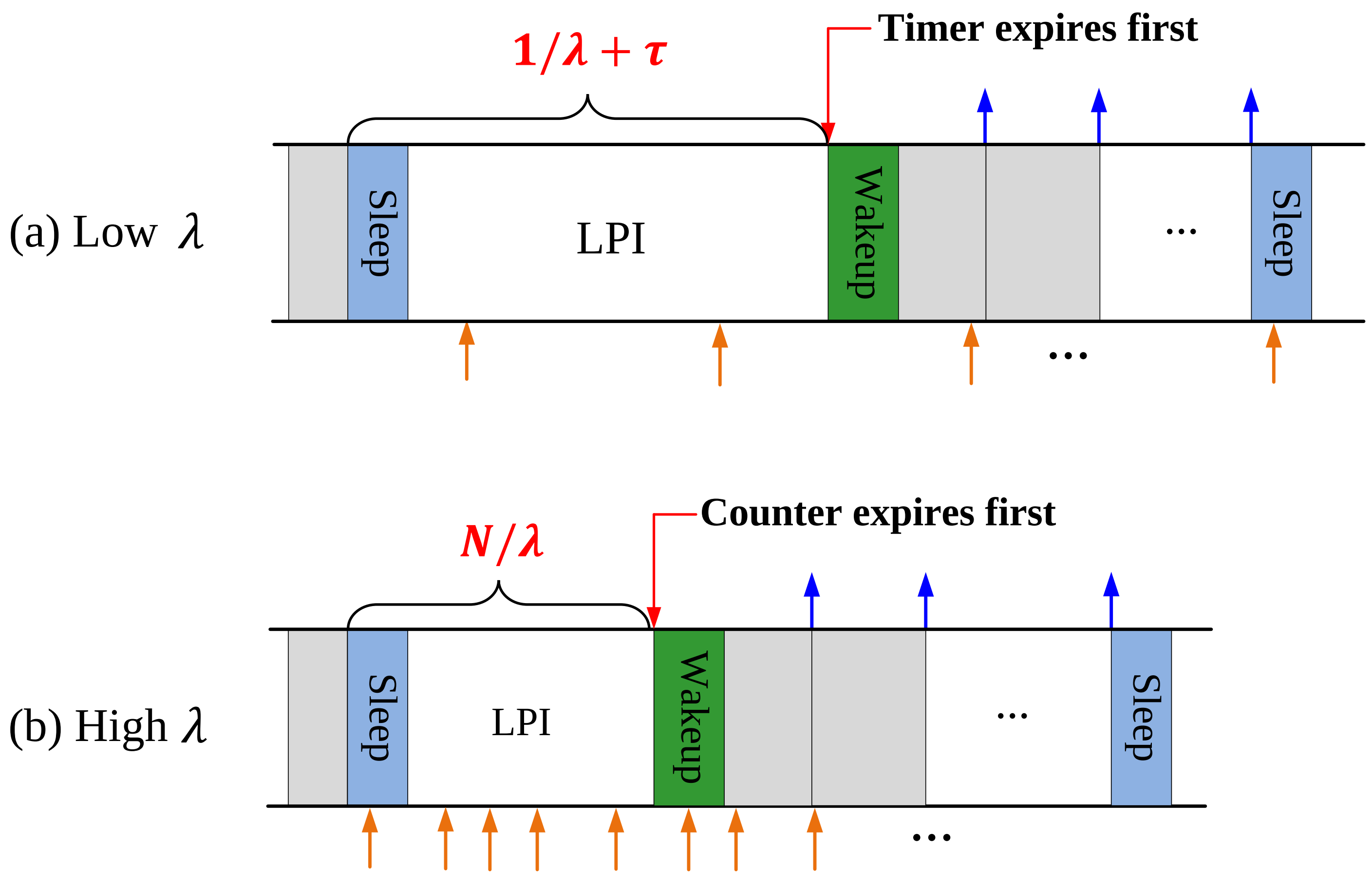
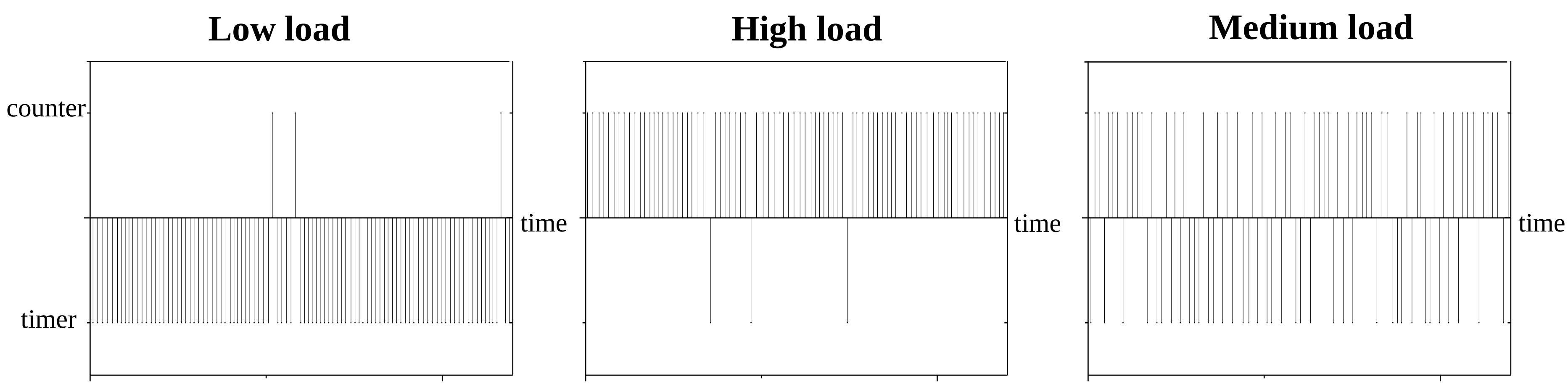
Tradeoff: Timer versus Counter



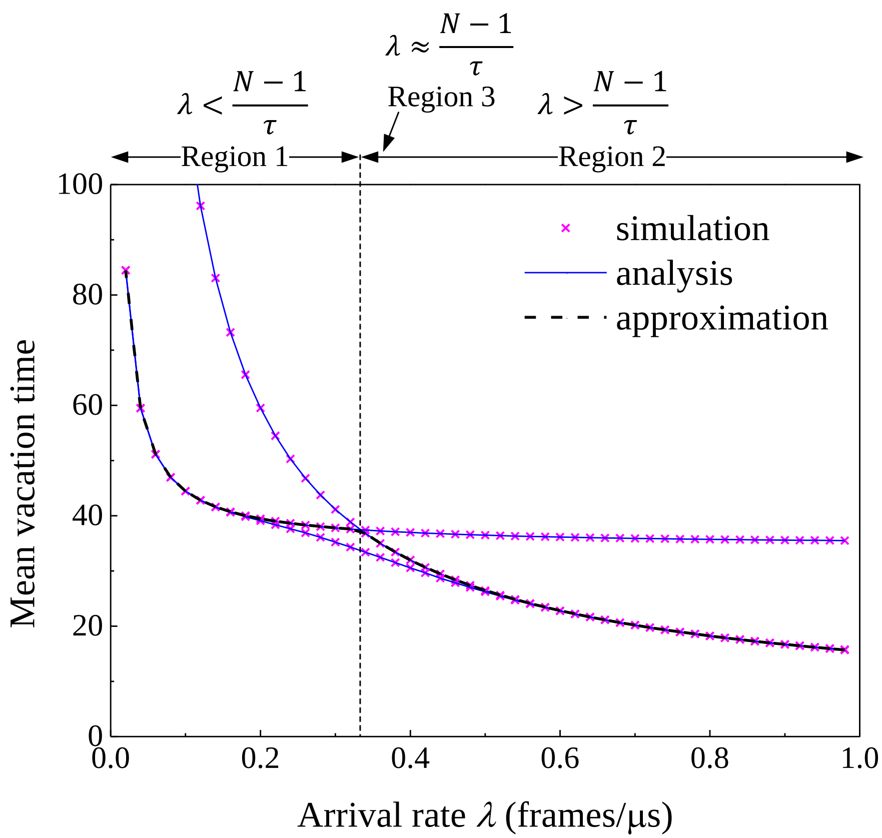
Tradeoff: Timer versus Counter

- Low load: $\lambda < \frac{N-1}{\tau},\ \bar{V} \approx \frac{1}{\lambda} + \tau + T_w$
- High load: $\lambda > \frac{N-1}{\tau}, \bar{V} \approx \frac{N}{\lambda} + T_w$
- Medium load: $\lambda \approx \frac{N-1}{\tau}, \bar{V} \geq \frac{1}{\lambda} + \tau + T_w \approx \frac{N}{\lambda} + T_w$



Approximation of Mean Vacation Time

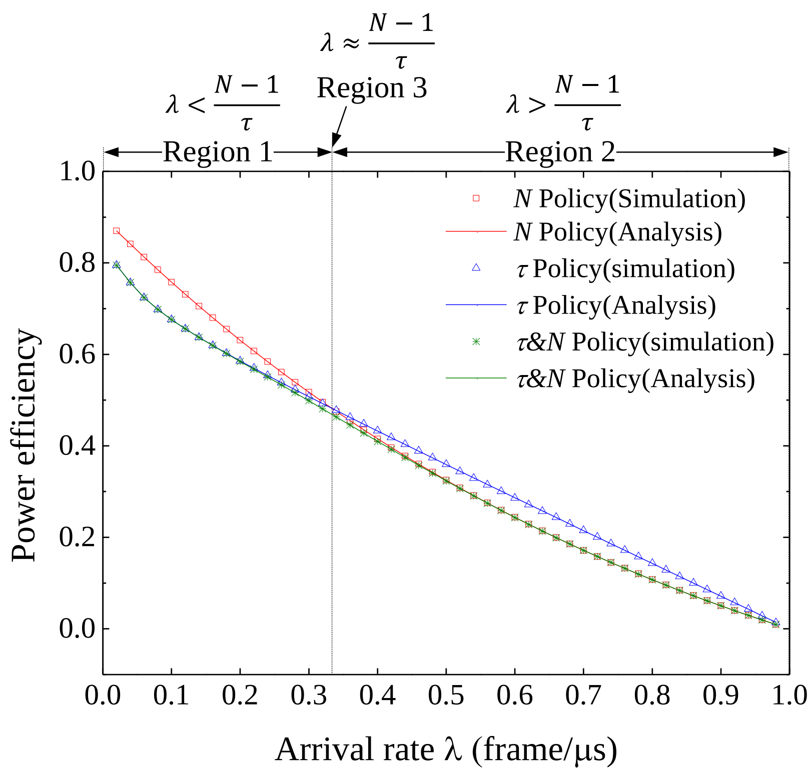
$$\bar{V} \approx min\{\bar{V}_\tau, \bar{V}_N\} = min\left\{\frac{1}{\lambda} + \tau, \frac{N}{\lambda}\right\} + T_w$$

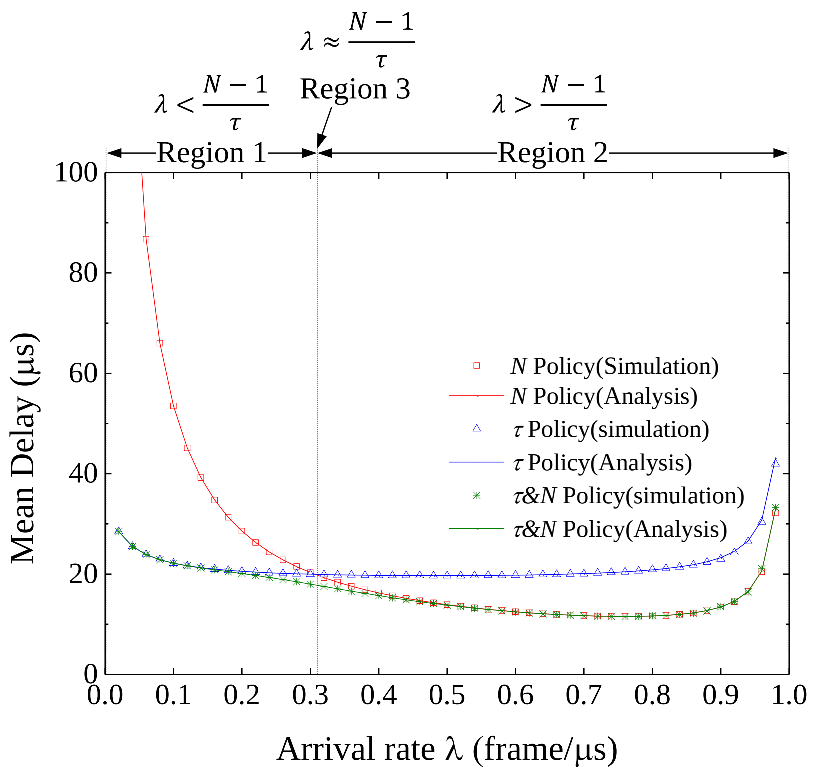


Approximation of Performances

$$\eta \approx min\{\eta_\tau, \eta_N\} = min\left\{1 - \frac{T_S+T_W}{\frac{1}{\lambda}+\tau+T_W}, 1 - \frac{T_S+T_W}{\frac{N}{\lambda}+T_W}\right\} \times \frac{(1-\rho)\times(\varphi_h-\varphi_l)}{\varphi_h}$$

$$D \approx min\{D_\tau, D_N\} = min\left\{\frac{(\lambda\tau+\lambda T_W)^2+2(\lambda\tau+\lambda T_W)}{2\lambda(1+\lambda\tau+\lambda T_W)}, \frac{(N+\lambda T_W)^2-N}{2\lambda(N+\lambda T_W)}\right\} + \frac{\lambda\overline{X^2}}{2(1-\rho)} + \bar{X}$$



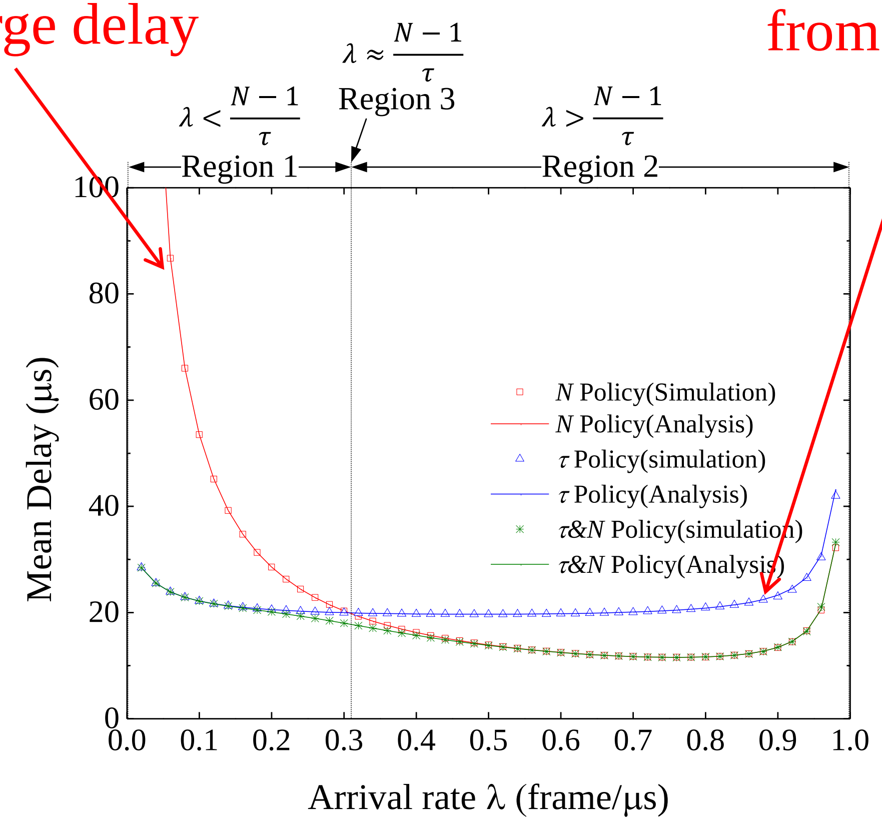


Optimal Relation of Timer and Counter

- $\tau \& N$ policy can adapts to traffic fluctuations and avoids large delays, especially in two side regions.

N policy suffers from a large delay

τ policy suffers from a large delay



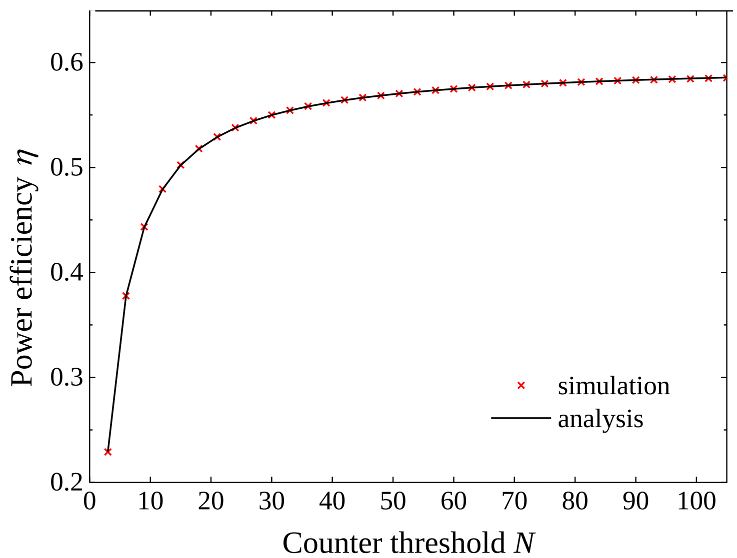
Rule EEE 1

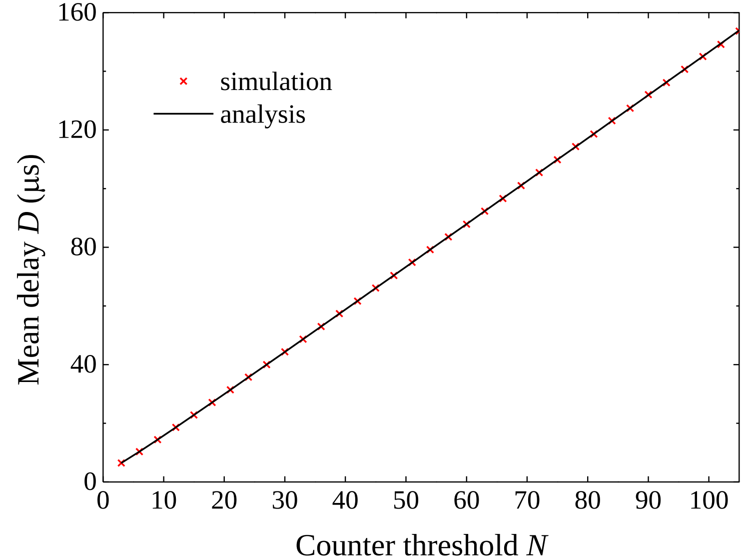
EEE 1: For a given steady state traffic rate λ, the selection of parameters τ and N should comply with the following condition:

$$\frac{N-1}{\tau} = \lambda.$$

Power Efficiency versus Mean Delay

- Excessive large τ and N degrade delay performance while marginally enhancing the power efficiency.
  - (a) With the increase of $\tau, N,\ \bar{V} \to \infty$ and $\eta \to \eta^*$
  - (b) D is almost linearly proportional to τ and N





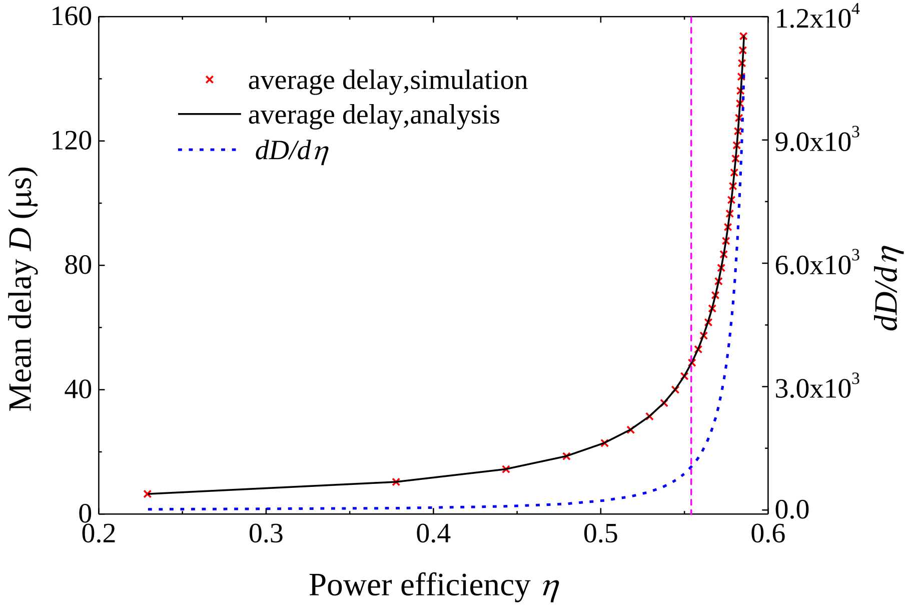
Power Efficiency versus Mean Delay

- Mean delay: a function of the power efficiency

$$D \approx \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{T_s+T_w}{2\left(1-\frac{\eta}{\eta^*}\right)} - \frac{T_s+T_w\frac{\eta}{\eta^*}}{2\lambda(T_s+T_w)} + \bar{X},$$

- The derivative

$$\frac{dD}{d\eta} \approx \frac{T_s+T_w}{2\eta^*\left(1-\frac{\eta}{\eta^*}\right)^2} - \frac{T_w}{2\lambda\eta^*(T_s+T_w)}$$



Rule EEE 2

EEE 2: Parameter N of the EEE protocol can be selected according to a given average delay requirement D from the expression of D_N.

$$D_N \approx \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{(N+\lambda T_w)^2 - N}{2\lambda(N+\lambda T_w)} + \bar{X}$$

Conclusions

- Develop a new approach to analyze the $M/G/1$ queue with the vacation time that is governed by the arrival process and the parameters τ and N.
- Derive a generalized P-K formula of mean delay

$$D = \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{H''(1)}{2\lambda H'(1)} + \bar{X}$$

- Provide two rules to select appropriate τ and N.
  - EEE 1

$$\frac{N-1}{\tau} = \lambda$$

  - EEE 2

$$D_N \approx \frac{\lambda \overline{X^2}}{2(1-\rho)} + \frac{(N+\lambda T_W)^2 - N}{2\lambda(N+\lambda T_W)} + \bar{X}$$

Thanks for your attention

Our work has been uploaded to arXiv.org and is available at https://arxiv.org/abs/1611.04394