# Efficient teletraffic models for optimizing the performance of communication networks

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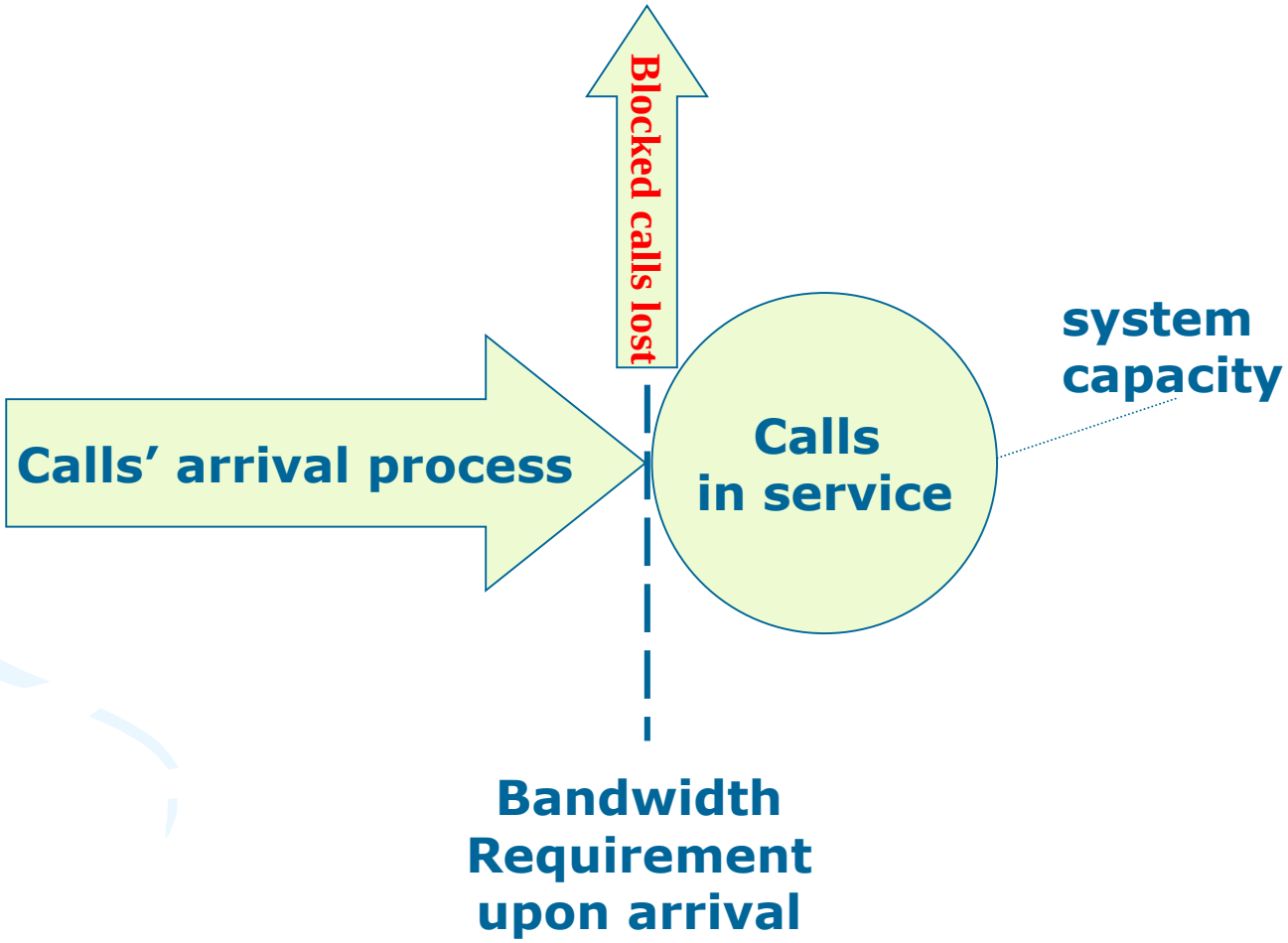
# Preamble

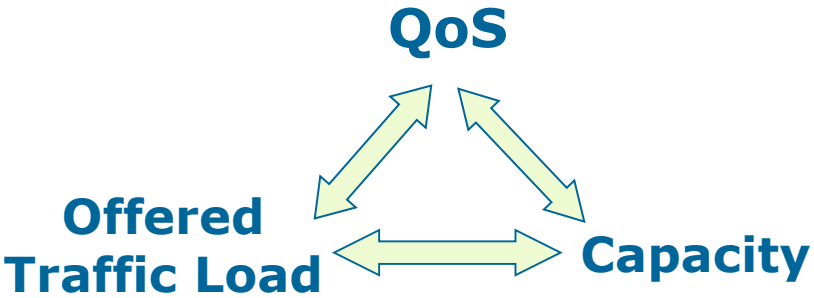
**A Loss Service System**

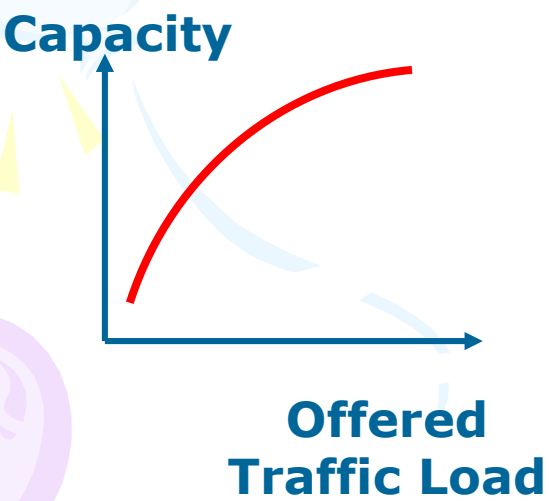


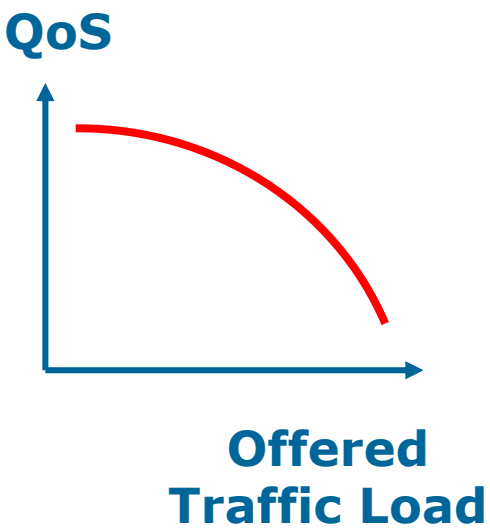
# Preamble (cont.)

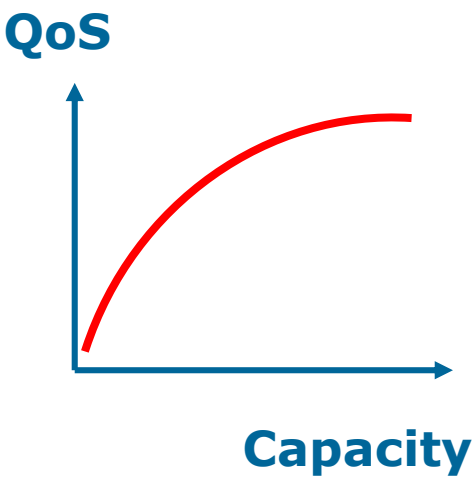
*Teletraffic Loss Models*

*Models = mathematical formulas*



# Preamble (cont.)

***Performance-oriented network management***

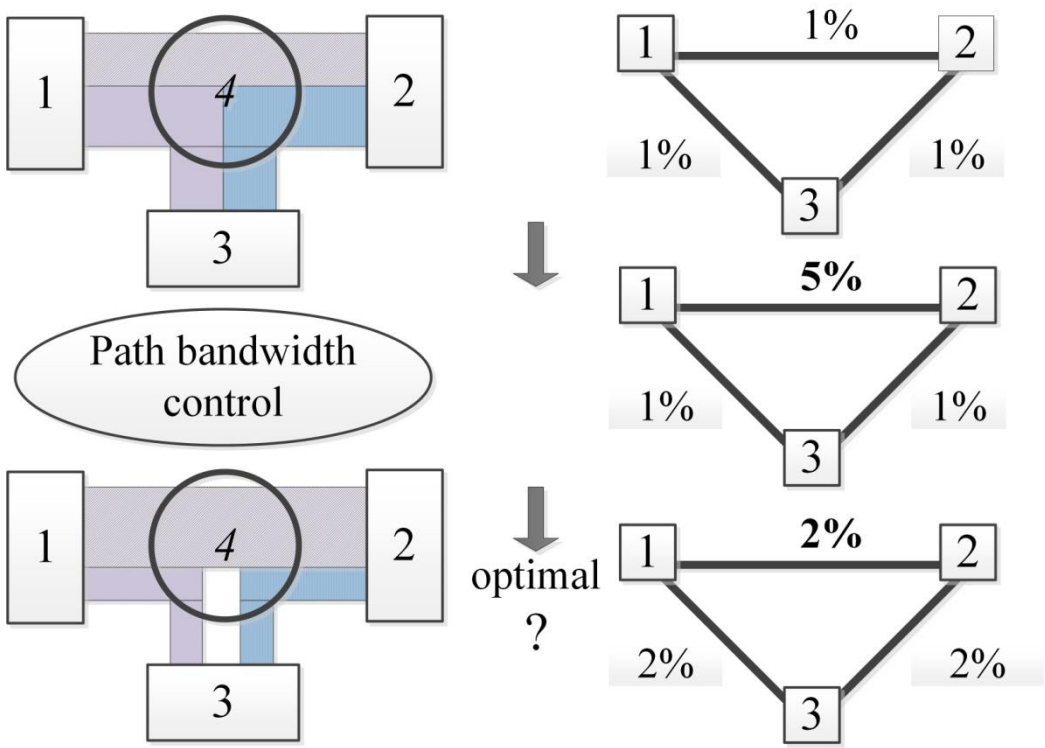
- Periodical performance evaluation (based on traffic measurements) and
- Adaptive resource assignment
  - **most suitable strategy for network planning under demand uncertainty**

***Nature of traffic***

- No single/constant rate
  - very different bandwidth per call requirements
  - several alternative contingency bandwidth requirements (e.g., multimedia traffic)
- In-service calls may
  - have adaptive features of bandwidth and holding time
  - experience bandwidth compression-expansion
- Random - Bursty traffic
  - Poisson arrivals
  - Quasi-random arrivals
  - ON-OFF traffic
  - Batched Poisson arrivals

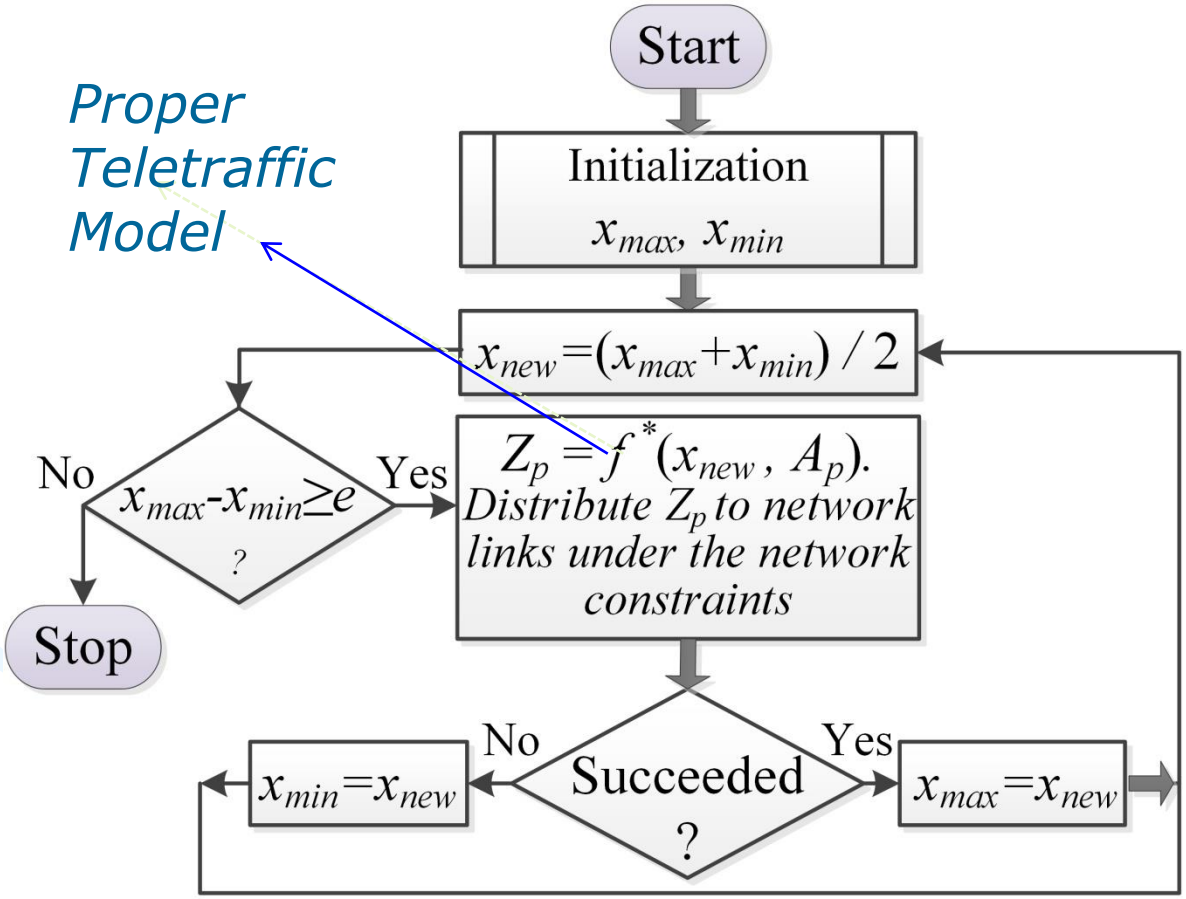
# Performance-oriented network management

## *The Problem*



# Performance-oriented network management

## *Global network optimization – Algorithm*



# Teletraffic Models – Why?

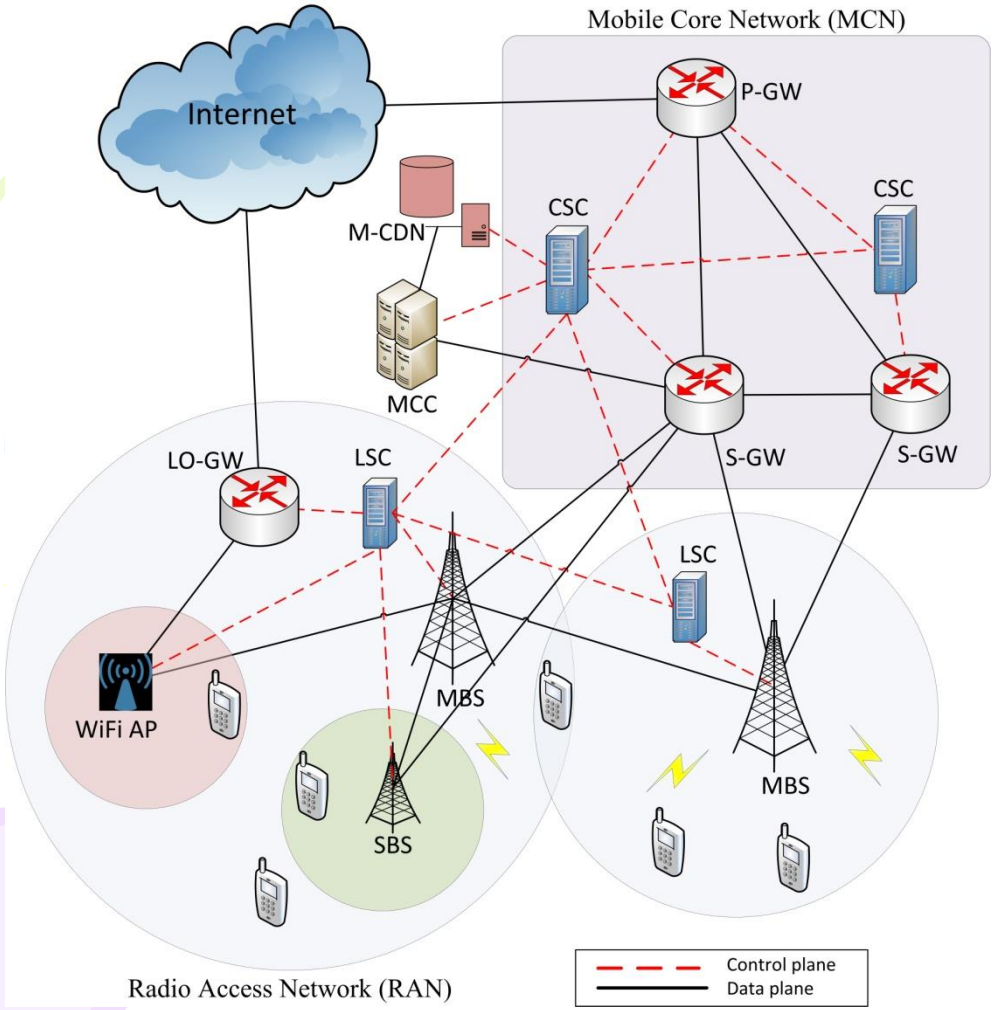
- **Importance of QoS assessment through teletraffic models:**
  - **Bandwidth allocation among service-classes → QoS per service guarantee.**
  - **Avoidance of too costly over-dimensioning of the network.**
  - **Prevention of excessive network throughput degradation, through traffic engineering mechanisms.**

- **A sine qua non of teletraffic loss models:**

  **The efficient calculation of Call Blocking Probability → Recursive formula.**

- **Applicability:**
  - **Connection Oriented Communication Networks, in general.**
  - **IP based networks with resource reservation capabilities (IntServ - DiffServ).**
  - **Cellular networks (e.g., UMTS).**
  - **All-optical core networks (MPλS/GMPLS).**
  - **5G networks.**

# Applicability to SDN-based 5G networks
# SDN/NFV based 5G architecture

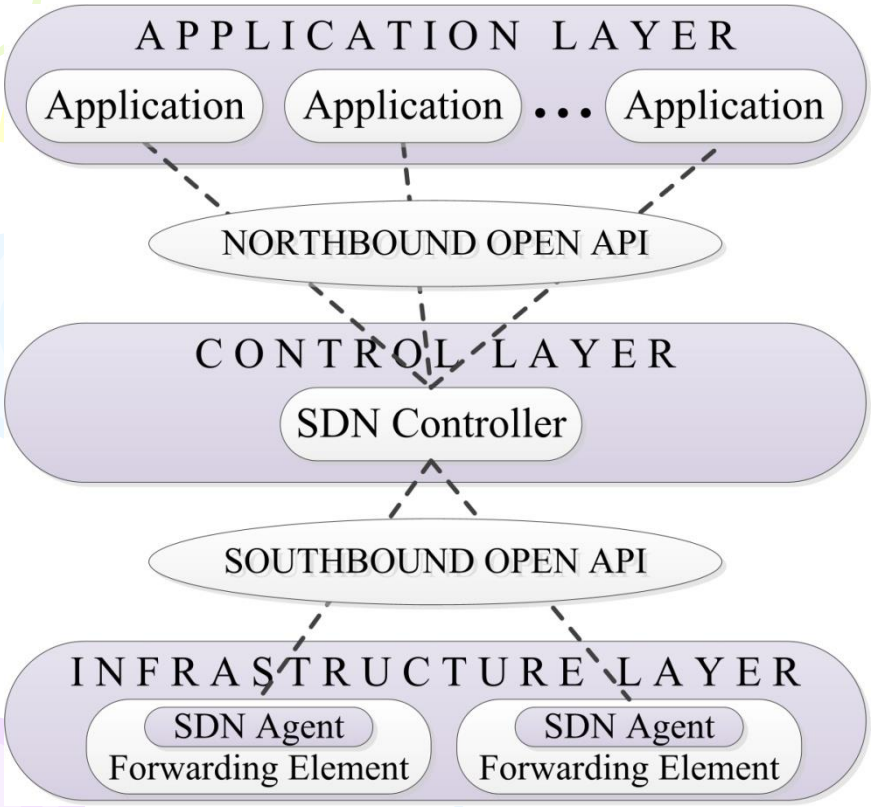



Software Defined Network (SDN):
*completely programmable network by decoupling the control and data planes.*

Network Function Virtualization (NFV):
*allows executing the SDN functions on general-purpose hardware, reducing the network cost.*

P-GW – Packet Data Network Gateway
CSC – Core SDN Controller
LSC – Local SDN Controller
S-GW – Serving Gateway
M-CDN – Mobile Content Delivery Network
MCC – Mobile Cloud Computing
MBS – Macro cell Base Station
SBS – Small cell Base Station
WiFi AP – Access Point with WiFi protocol
LO-GW – Local Offload Gateway
MU – Mobile User

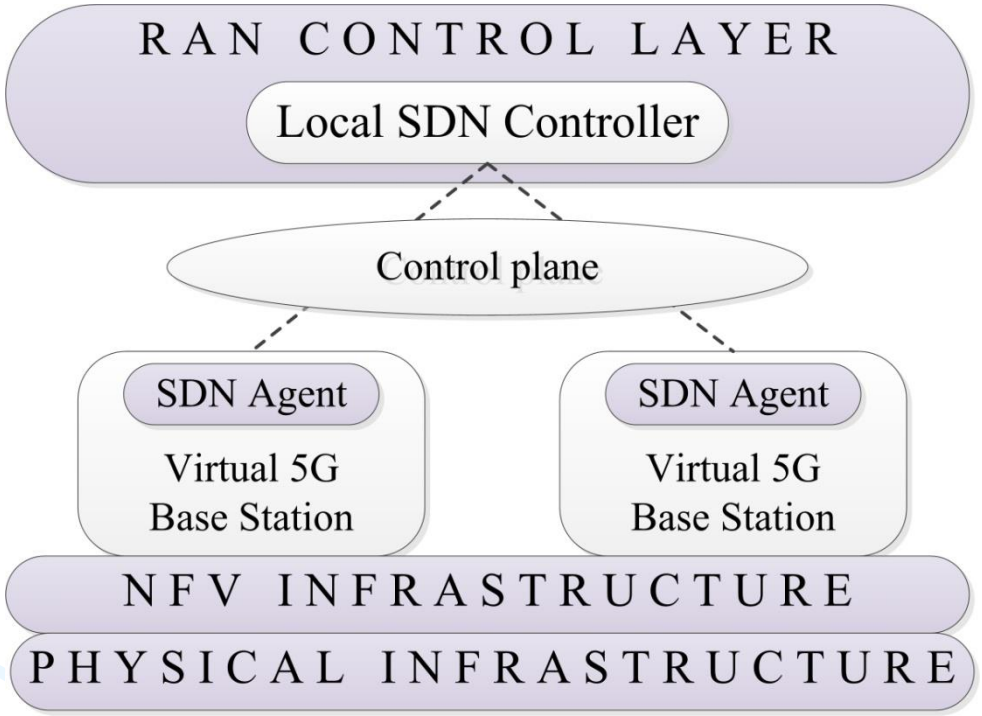
# Applicability to SDN-based 5G networks
# Layering concept in SDN



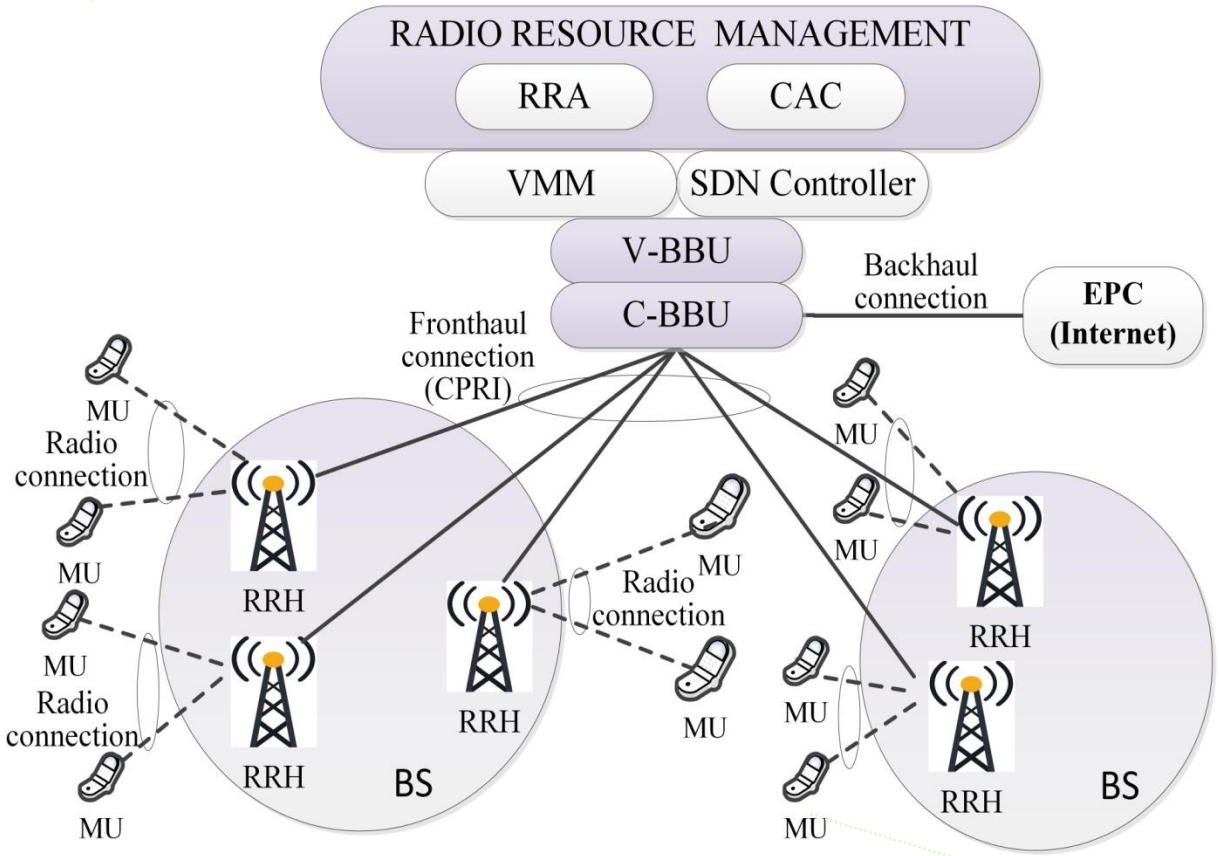

The SDN controller provides a global view of the available underlying resources to network applications (Application Layer) by the Northbound Open API.

The SDN controller configures the Forwarding Elements (located at the Infrastructure Layer) by sending control messages to the SDN Agents (located within the FEs) through the Southbound Open API.

# Applicability to SDN-based 5G networks SDN/NFV based RAN



# Applicability to SDN-based 5G networks Cloud-RAN architecture




RRA – Radio Resource Allocation

CAC – Connection Admission Control

VMM – Virtual Machine Monitor

V-BBU – Virtual BaseBand Units (signal processing servers)

C-BBU – Centralized BaseBand Units (central pool of data center resources)

EPC – Evolved Packet Core

CPRI – Common Public Radio Interface

RRH – Remote Radio Head (radio frequency components–antennas)

BS – Base Station

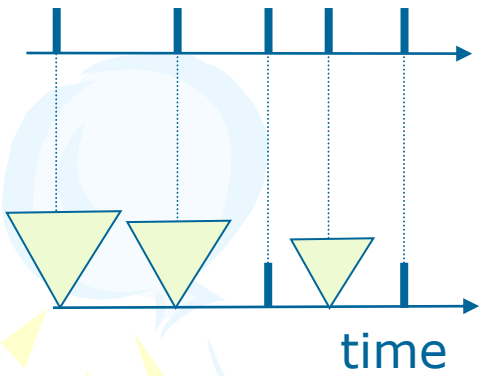
A call requires a radio resource unit from RRH and a computational resource unit from V-BBU. CAC checks the availability of resources to accept the call.

# Classification of teletraffic models

**Key considerations:**

- The call arrival process.
- The service-classes
  - Bandwidth requirement upon call arrival.
  - The behavior of in-service calls regarding the amount of occupied b.u. per call over time.
- Bandwidth sharing policy
  - Complete sharing policy
  - Bandwidth/Trunk reservation policy
  - Threshold Policy

# Call Arrival Process

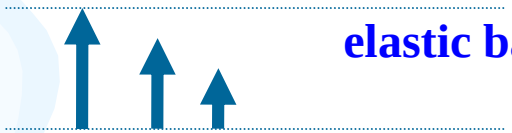



- **Random arrivals – traffic *(infinite number of traffic sources)*.**
- **Quasi-random arrivals – traffic *(finite number of traffic sources)*.**

- **Batched Poisson arrivals *(infinite number of traffic sources)*.**
  **Calls from different service-classes arriving in batches, while batches arriving randomly.**

# Bandwidth requirement upon call arrival

**fixed bandwidth**



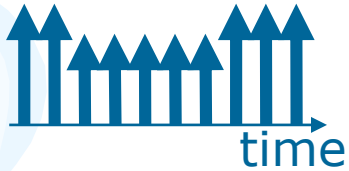
**elastic bandwidth**: *calls have several, alternative, contingency bandwidth requirements*

# Call's behavior while in service

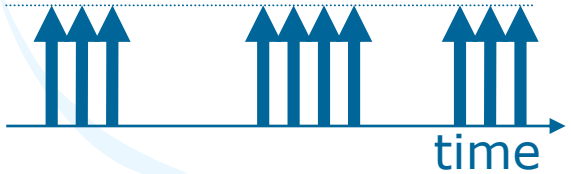


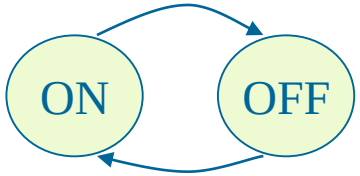


**constant-bit-rate (stream traffic)**




**bandwidth compression/expansion (elastic traffic)**



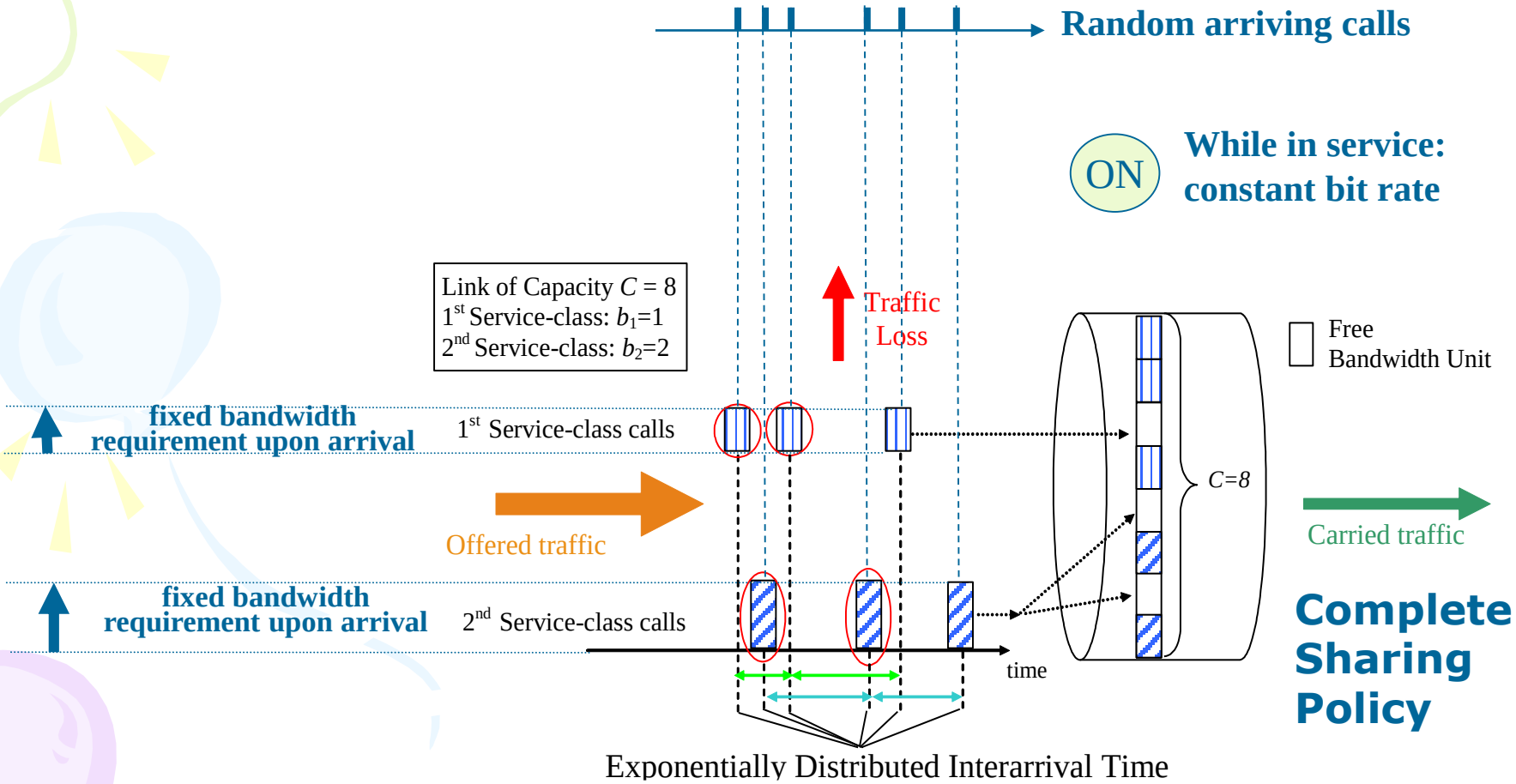




**ON-OFF traffic**

# Efficient teletraffic loss models

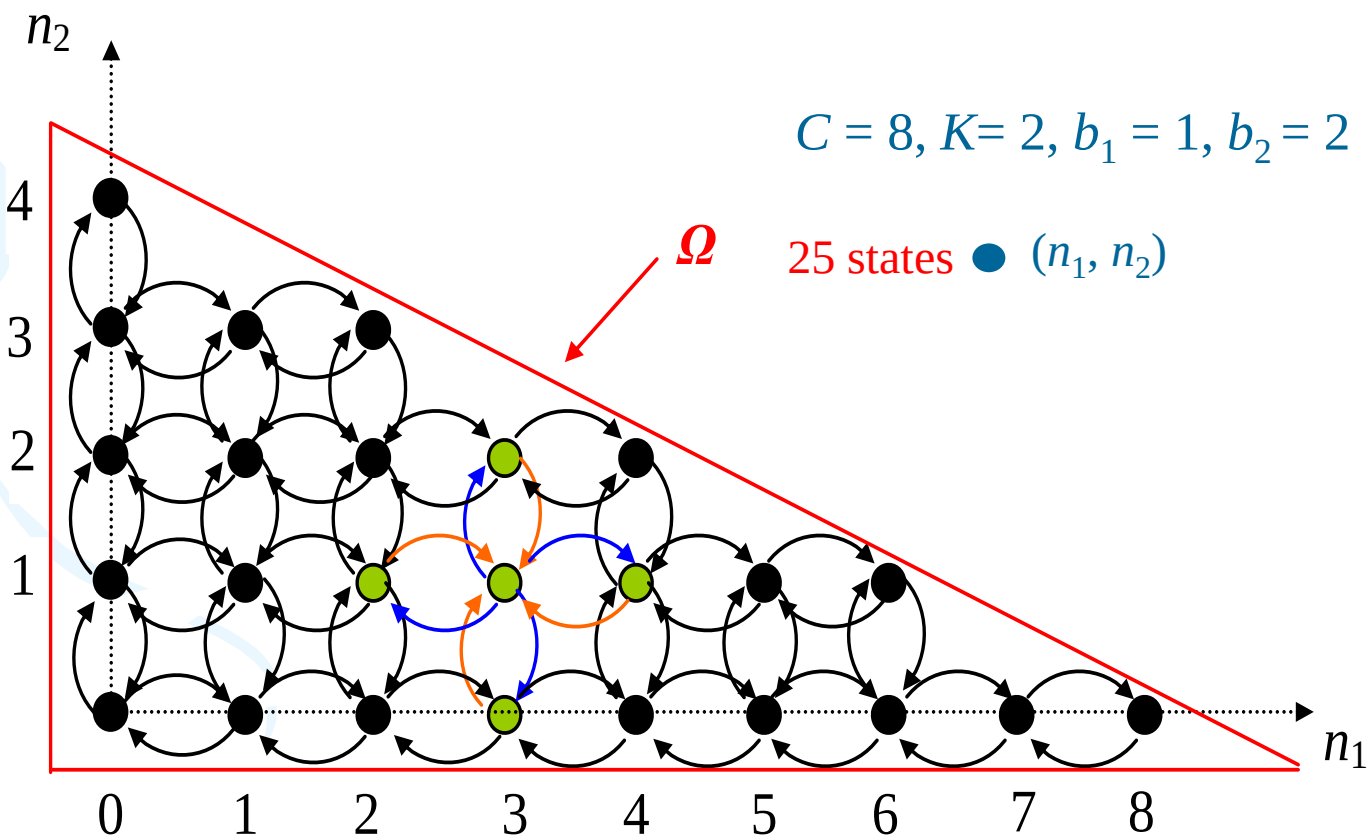
- **Teletraffic models of random input**
  - Random arriving calls with fixed or elastic bandwidth requirements, and *fixed bandwidth allocation during service*.
  - Random arriving calls with fixed or elastic bandwidth requirements, and *elastic bandwidth during service*.
  - Random arriving calls with fixed or elastic bandwidth requirements, and *ON–OFF traffic behavior during service*.

# The Erlang Multi-rate Loss Model (EMLM)



# EMLM Analysis – Classical Method

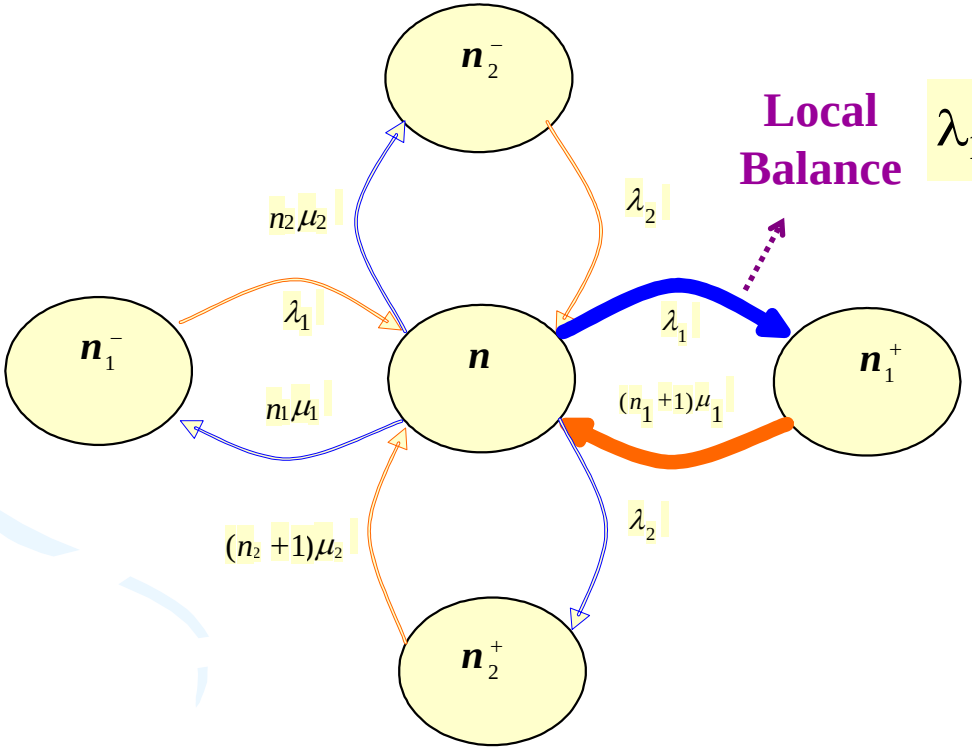
**State Space $\Omega$**
**Complete Sharing Policy – A coordinate convex policy**
**Global Balance (rate_in=rate_out) - Statistical equilibrium**



# EMLM Analysis – Classical Method (cont.1)

**Global Balance (Rate_in = rate_out)**

**Local Balance (Rate_up = rate_down)**




**Local Balance**

$$\lambda_1 P(\boldsymbol{n}) = (n_1+1)\mu_1 P(\boldsymbol{n}_1^+)$$

# EMLM Analysis – Classical Method (cont.2)

## Call Blocking Probability Determination – Classical Method

$K$=2, $b_1$ = 1, $b_2$ = m

Example of formulas for Call Blocking Probability Calculation

$$P_{b_1} = P_{00} \sum_{j=0}^{s} \frac{\alpha_1^{C-mj}}{(C-mj)!} \frac{\alpha_2^{j}}{j!}$$

$$P_{b_2} = P_{00} \left( \frac{\alpha_2^{2}}{s!} \sum_{i=0}^{k} \frac{\alpha_1^{i}}{i!} + \sum_{j=0}^{s-1} \sum_{i=C-mj-m+1}^{C-mj} \frac{\alpha_1^{i}}{i!} \frac{\alpha_2^{j}}{j!} \right)$$

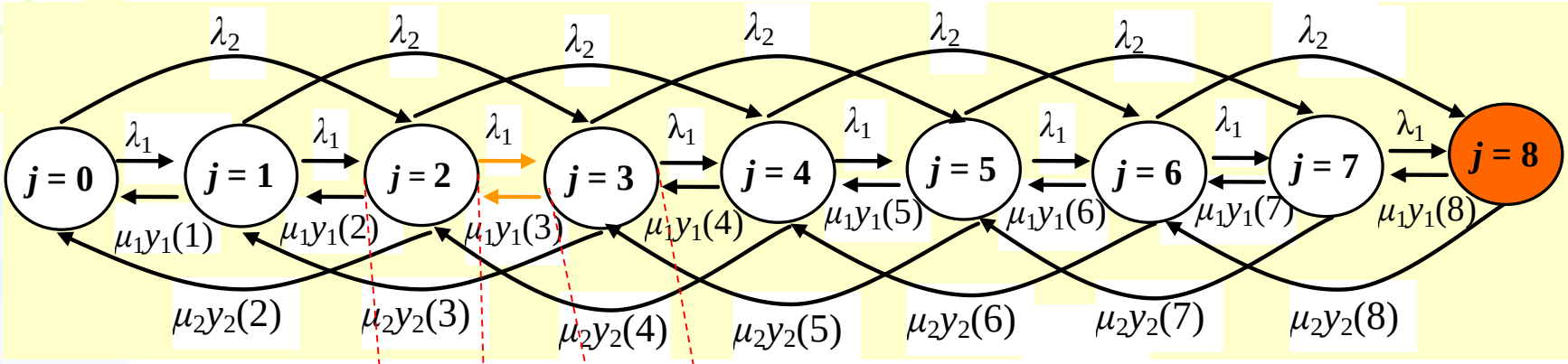
where k= C (mod m)

**(Necessity for recursive formulas)**

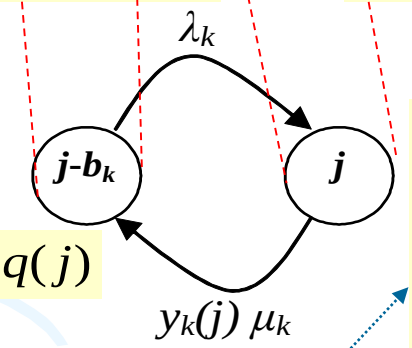
# EMLM Analysis – New Method

## Macro-states – One-dimensional Markov chain

$C = 8$, $K=2$, $b_1 = 1$, $b_2 = 2$ Macro-state $j=n_1b_1+n_2b_2$ denotes the total number of in-service calls




**local balance**




$$\lambda_k q(j-b_k) = y_k(j)\mu_k q(j)$$

**Link occupancy distribution**

Un-normalized

$$q(j) = \begin{cases} 1 & \text{for } j=0 \\ \frac{1}{j}\sum_{k=1}^{K} a_k b_k q(j-b_k) & \text{for } j=1,\ldots,C \\ 0 & \text{otherwise} \end{cases}$$

**"Kaufman / Roberts Recursion"**

# EMLM Analysis – New Method (cont.)

## Call Blocking Probability – Recursive Calculation

**Call Blocking Probability:** $$P_{b_k} = \sum_{j=C-b_k+1}^{C} G^{-1} q(j) \quad \text{where} \quad G = \sum_{j=0}^{C} q(j)$$

**Accurate calculation especially when service-classes have equal mean service times!**

**q(j)/G – Macro-state Probabilities**

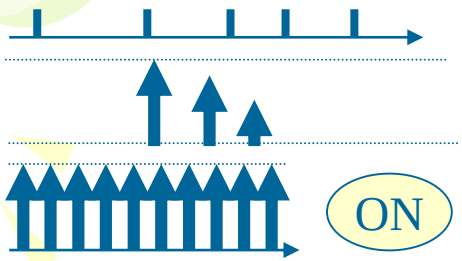
**array q()** **Blocking State, e.g. $b_k$=1**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | ... | C-4 | C-3 | C-2 | C-1 | C |

**Blocking States, e.g. $b_k$=4**

**Link Utilization:** $$U = \sum_{j=1}^{C} j\, q(j)$$

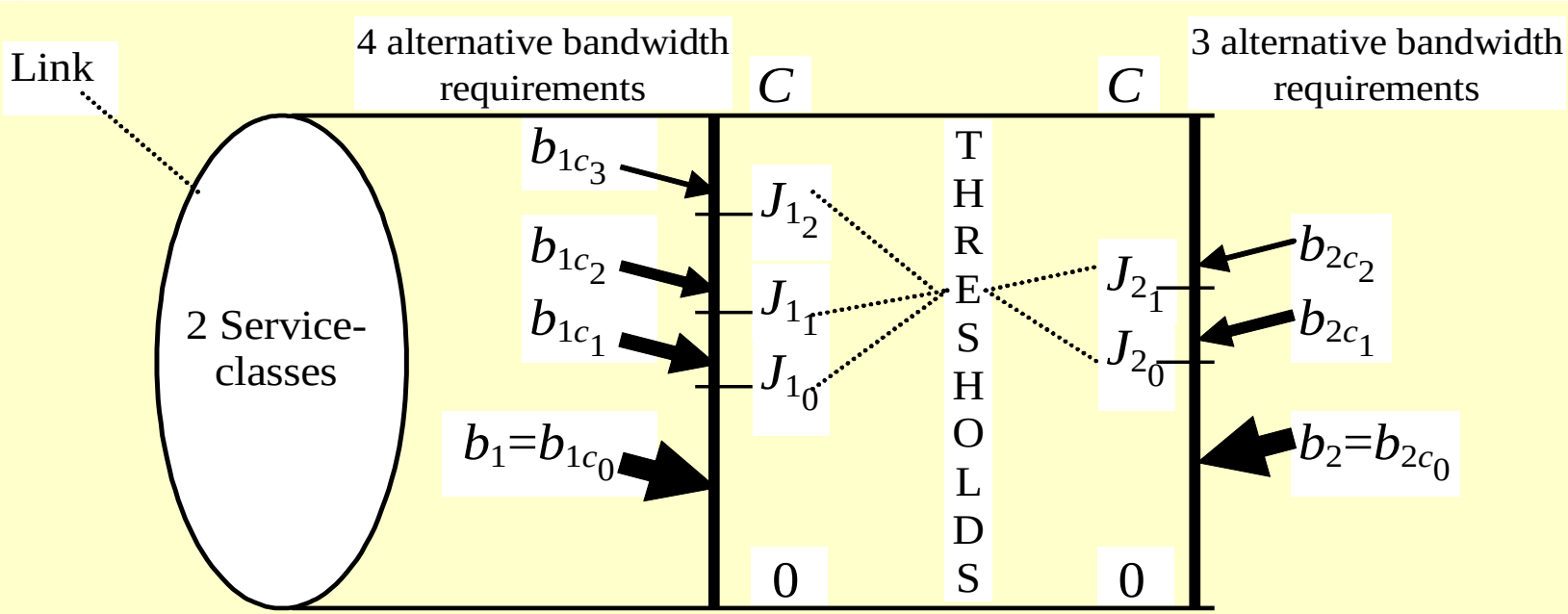
# The Connection Dependent Threshold Model (CDTM)




**Random arrivals**

**Elastic bandwidth requirements**

**Constant bit rate (stream traffic)**




Local Balance ⇒ Product Form Solution ⇒ $\approx P_{bk}$

# CDTM - The analytical model

**Assumptions – Approximations**

1) **Local Balance**
2) **Migration Approximation, M.A** $(\delta_{kc_s}(j))$
3) **Upward migration Approximation, U.A** $(\delta_k(j))$

$$q(j)=\begin{cases}1 & for\ \ j=0\\ \frac{1}{j}\left(\sum_{k=1}^{K}a_k b_k \delta_k(j) q(j-b_k)+\sum_{k=1}^{K}\sum_{s=1}^{S(k)}a_{kc_s}b_{kc_s}\delta_{kc_s}(j)q(j-b_{kc_s})\right) & for\ \ j=1,\dots,C\\ 0 & otherwise\end{cases}$$

$$a_{kc_s}=\lambda_k\mu_{kc_s}^{-1}$$

$$\delta_k(j)=\begin{cases}1 & (\text{if } 1\le j\le J_{k0}+b_k \text{ and } b_{kc_s}>0) \text{ or } (\text{if } 1\le j\le C \text{ and } b_{kc_s}=0)\\ 0 & \text{otherwise}\end{cases}$$

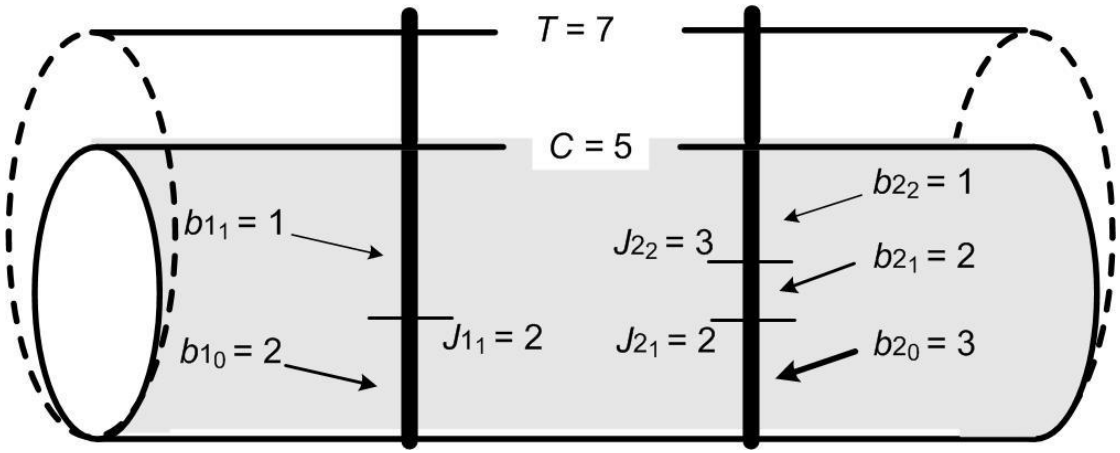
**U.A**

$$\delta_{kc_s}(j)=\begin{cases}1 & \text{if } J_{ks}+b_{kc_s}\ge j>J_{ks-1}+b_{kc_s} \text{ and } b_{kc_s}>0\\ 0 & \text{otherwise}\end{cases}$$

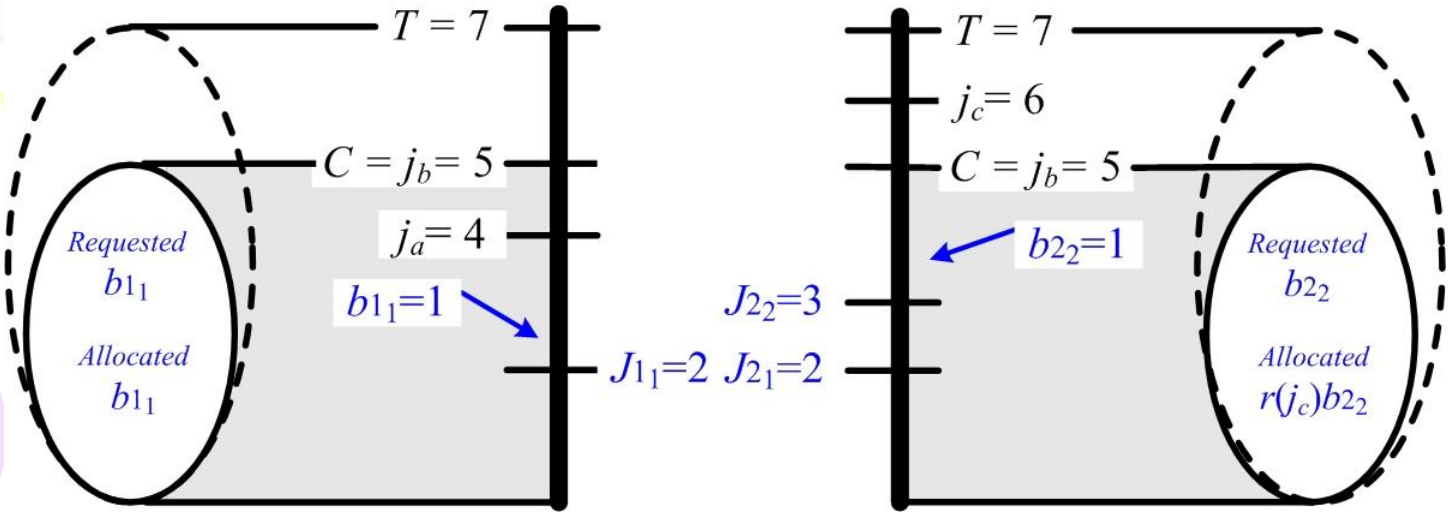
**M.A**

**Call Blocking Probability**: $P_{b_k}=\sum_{j=C-b_{kc_{S(k)}}+1}^{C}G^{-1}q(j)$ where $G=\sum_{j=0}^{C}q(j)$

# The Extended Connection Dependent Threshold Model (E-CDTM)




example




**Compression rate=C/j= 5/6**

# E-CDTM – The analytical model for elastic and adaptive service-classes

## Link occupancy distribution

$$q(j) = \begin{cases} 1 & \text{for } j = 0 \\ \dfrac{1}{\min(C, j)} \displaystyle\sum_{k \in K_e} \sum_{l=0}^{S_k} \alpha_{k_l} b_{k_l} \delta_{k_l}(j)\, q(j - b_{k_l}) + & \\ \quad + \dfrac{1}{j} \displaystyle\sum_{k \in K_a} \sum_{l=0}^{S_k} \alpha_{k_l} b_{k_l} \delta_{k_l}(j)\, q(j - b_{k_l}) & \text{for } j = 1, \ldots, T \\ 0 & \text{otherwise} \end{cases}$$

un-normalized

$$G = \sum_{j=0}^{T} q(j)$$

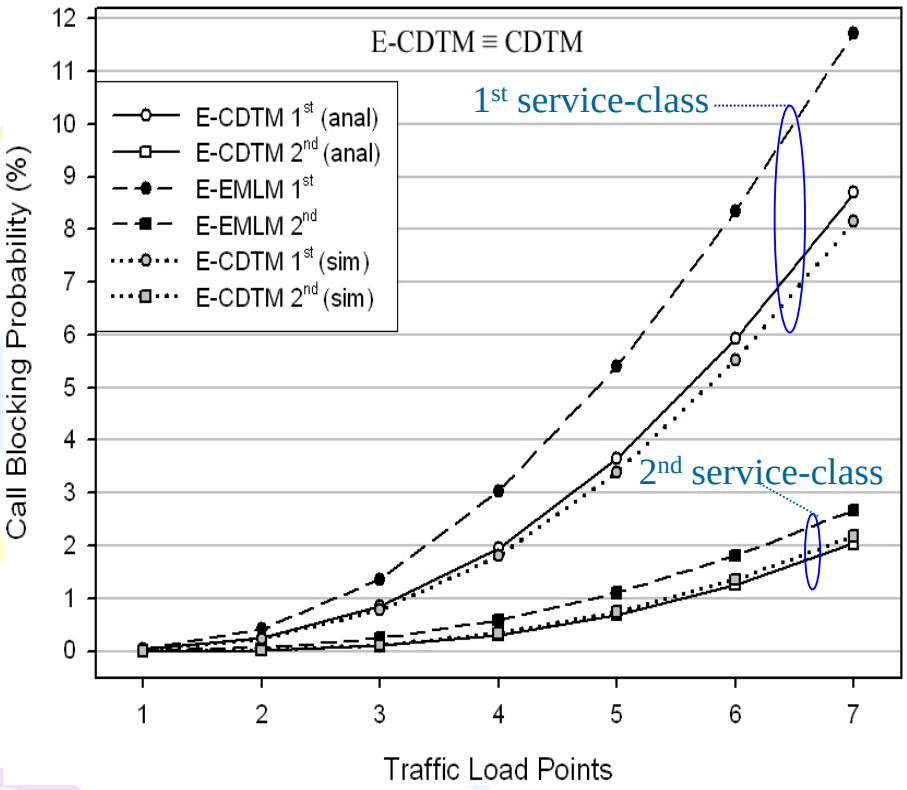
## Call Blocking Probability

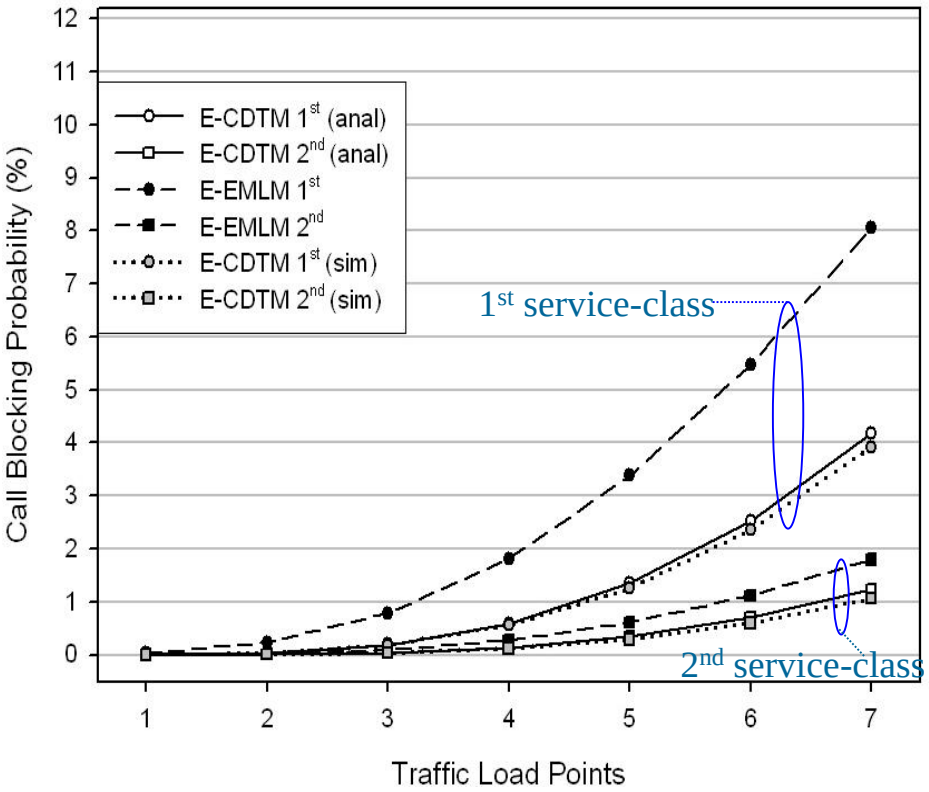
$$P_{b_k} = \sum_{j = T - b_{k_{S_k}} + 1}^{T} G^{-1} q(j)$$

## Link Utilization

$$U = \sum_{j=1}^{C} j G^{-1} q(j) + \sum_{j = C+1}^{T} G^{-1} C\, q(j)$$

# E-CDTM versus E-EMLM



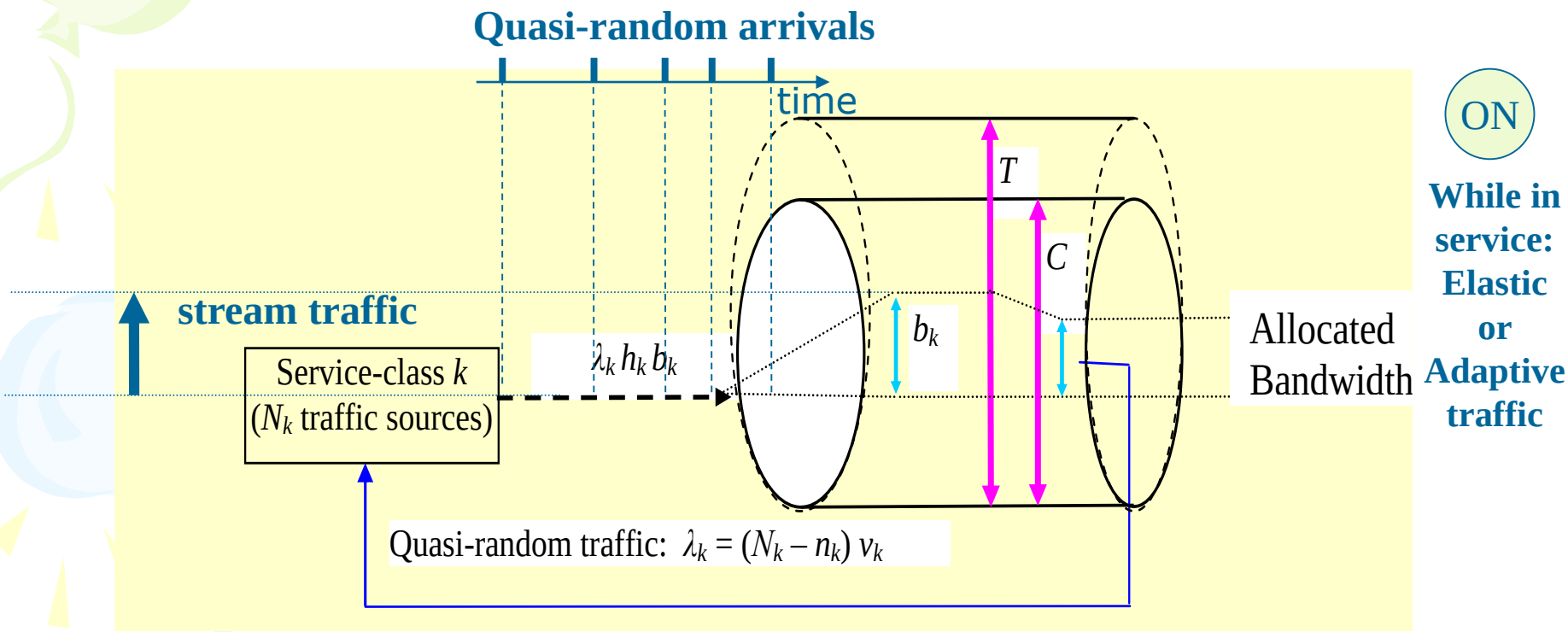

**C=T = 80**

**T = C + 10**

# Efficient teletraffic loss models (cont.1)

- **Teletraffic models of quasi-random input**
  - Quasi-random arriving calls with fixed or elastic bandwidth requirements and *fixed bandwidth allocation during service*.
  - Quasi-random arriving calls with fixed bandwidth requirements and *elastic bandwidth during service*.
  - Quasi-random arriving calls with fixed bandwidth requirements and *ON–OFF traffic behavior during service*.

# The Extended Engset Multi-rate Loss Model (E-EnMLM)




$h_k$ : holding (service) time of service-class $k$ calls

**If compression: "Bandwidth * Service-time" ⇒ constant ⇒ elastic traffic**

j : total bandwidth demand ($0 \le j \le T$)

T : maximum total bandwidth demand ($T \ge C$)

s : real bandwidth allocation ($0 \le s \le C$)

# E-EnMLM – The analytical model for elastic and adaptive service-classes

## Link occupancy distribution

$$q(j) = \begin{cases} 1 & \text{for } j = 0 \\ \dfrac{1}{\min(C, j)} \sum\limits_{k \in K_e} (N_k - n_k + 1)\alpha_k b_k q(j - b_k) + \\ + \dfrac{1}{j} \sum\limits_{k \in K_a} (N_k - n_k + 1)\alpha_k b_k q(j - b_k) & \text{for } j = 1, \ldots, T \\ 0 & \text{otherwise} \end{cases}$$

un-normalized

$$G = \sum_{j=0}^{T} q(j)$$

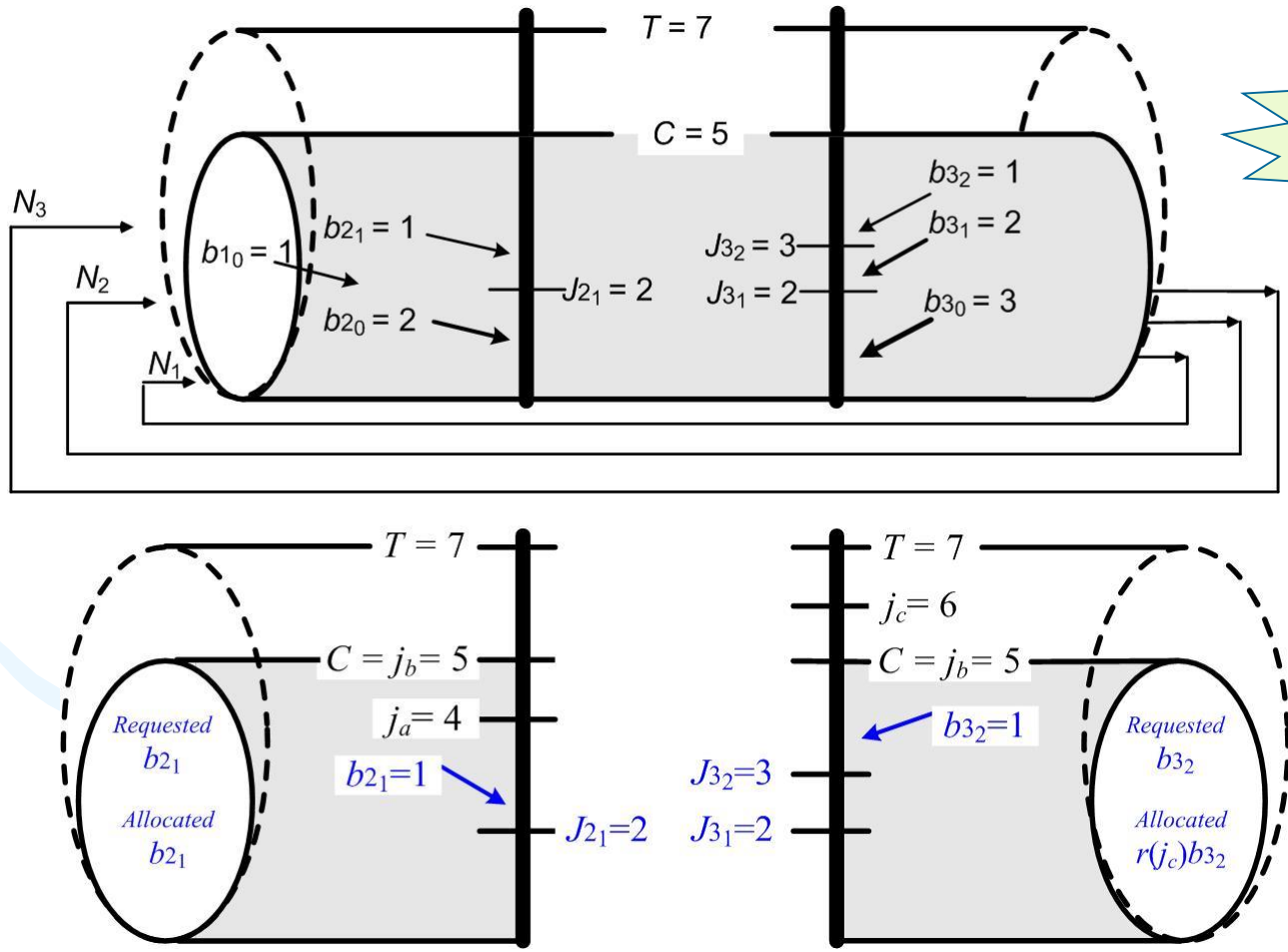
## Time Congestion Probability

$$P_{b_k} = \sum_{j=T-b_k+1}^{T} G^{-1} q(j)$$

## Link Utilization

$$U = \sum_{j=1}^{C} j G^{-1} q(j) + \sum_{j=C+1}^{T} G^{-1} C q(j)$$

# The Extended Connection Dependent Threshold Model for finite population (Ef-CDTM)




example

**Compression rate=C/j= 5/6**

# Ef-CDTM – The analytical model

## Link occupancy distribution

$$q(j)=\begin{cases}1 & \text{for } j=0\\ \dfrac{1}{\min(C,j)}\displaystyle\sum_{k\in K_e}\sum_{l=0}^{S_k}\left(N_k-\sum_{l=0}^{S_k}n_{k_l}+1\right)\alpha_{k_l}\,b_{k_l}\,\delta_{k_l}(j)\,q(j-b_{k_l})+ & \\ +\dfrac{1}{j}\displaystyle\sum_{k\in K_a}\sum_{l=0}^{S_k}\left(N_k-\sum_{l=0}^{S_k}n_{k_l}+1\right)\alpha_{k_l}\,b_{k_l}\,\delta_{k_l}(j)\,q(j-b_{k_l}) & \text{for } j=1,\ldots,T\\ 0 & \text{otherwise}\end{cases}$$

un-normalized

$$G=\sum_{j=0}^{T}q(j)$$

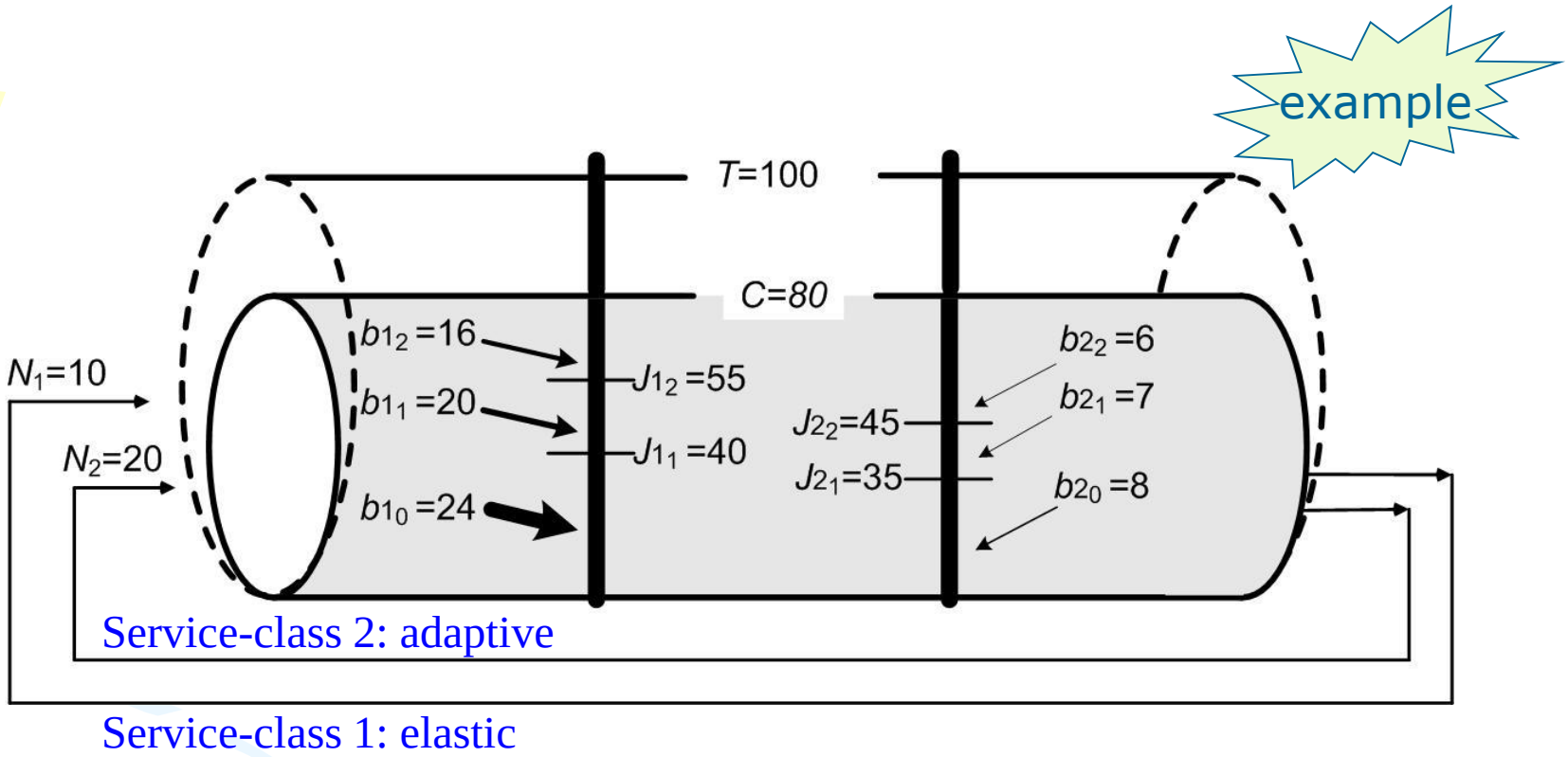
## Time Congestion Probability

$$P_{b_k}=\sum_{j=T-b_{k_{S_k}}+1}^{T}G^{-1}q(j)$$

## Link Utilization

$$U=\sum_{j=1}^{C}jG^{-1}q(j)+\sum_{j=C+1}^{T}G^{-1}Cq(j)$$

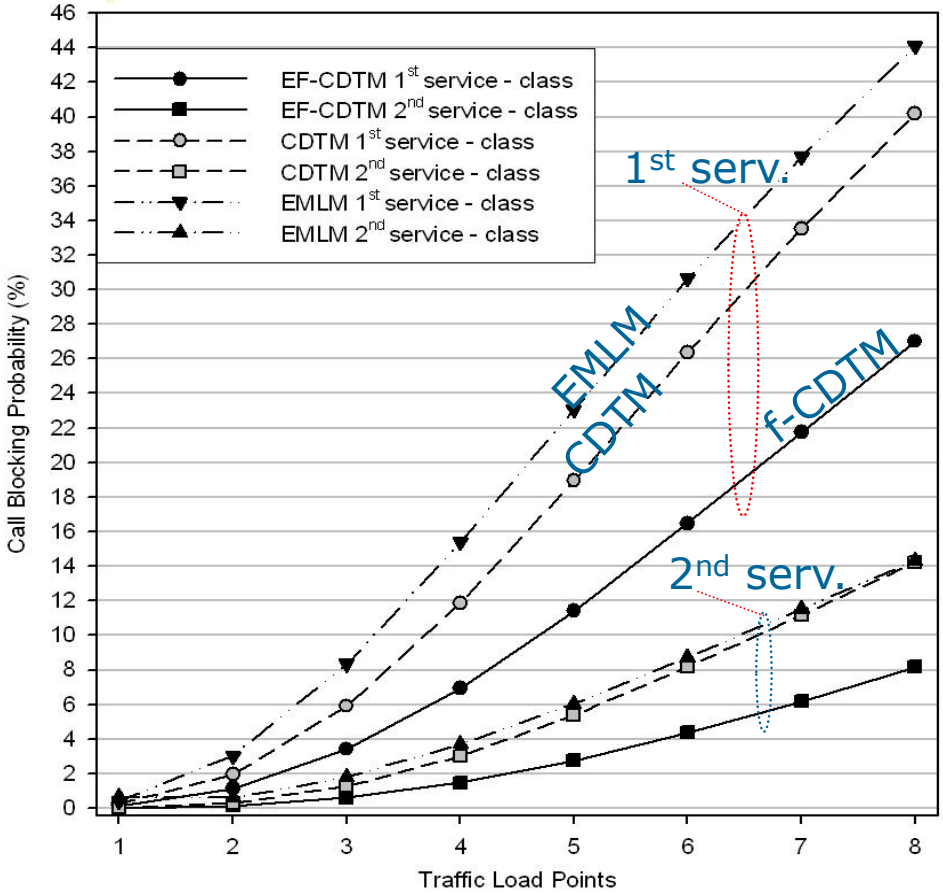
# Ef-CDTM comparison with other models: EMLM, CDTM, E-CDTM



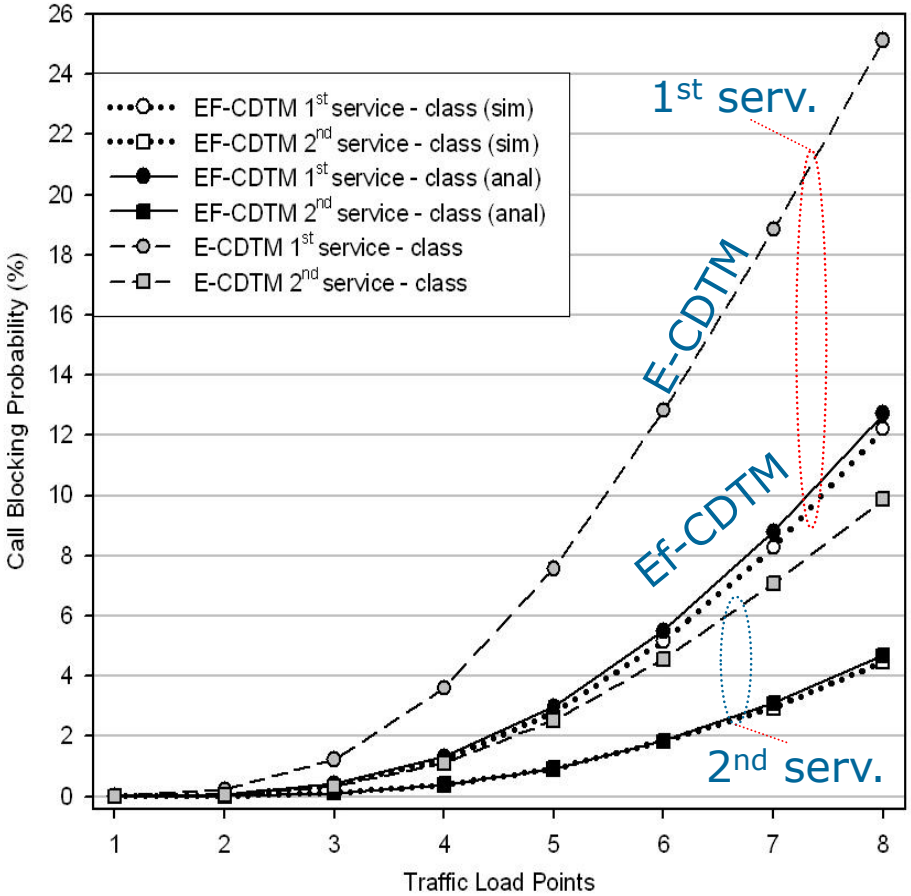

**Offered Traffic-Load per idle source = 0.025 erl**
**Consequently, it increases by 0.025 erl**

# Ef-CDTM comparison with other models: EMLM, CDTM, E-CDTM (cont.)

**T=C**



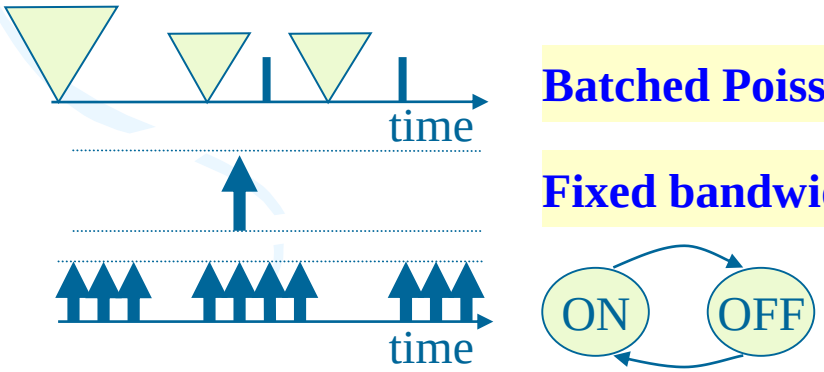

**T=C+20**




**Ef-CDTM ⟺ f-CDTM**

# Efficient teletraffic loss models (cont.2)

- **Teletraffic models of batched Poisson input**
  - Batched Poisson arriving calls with fixed bandwidth requirements and *fixed bandwidth allocation during service*.
  - Batched Poisson arriving calls with fixed bandwidth requirements and *elastic bandwidth during service*.
  - Batched Poisson arriving calls with fixed bandwidth requirements that, *when in service, alternate between transmission periods (ON) and idle periods (OFF).*



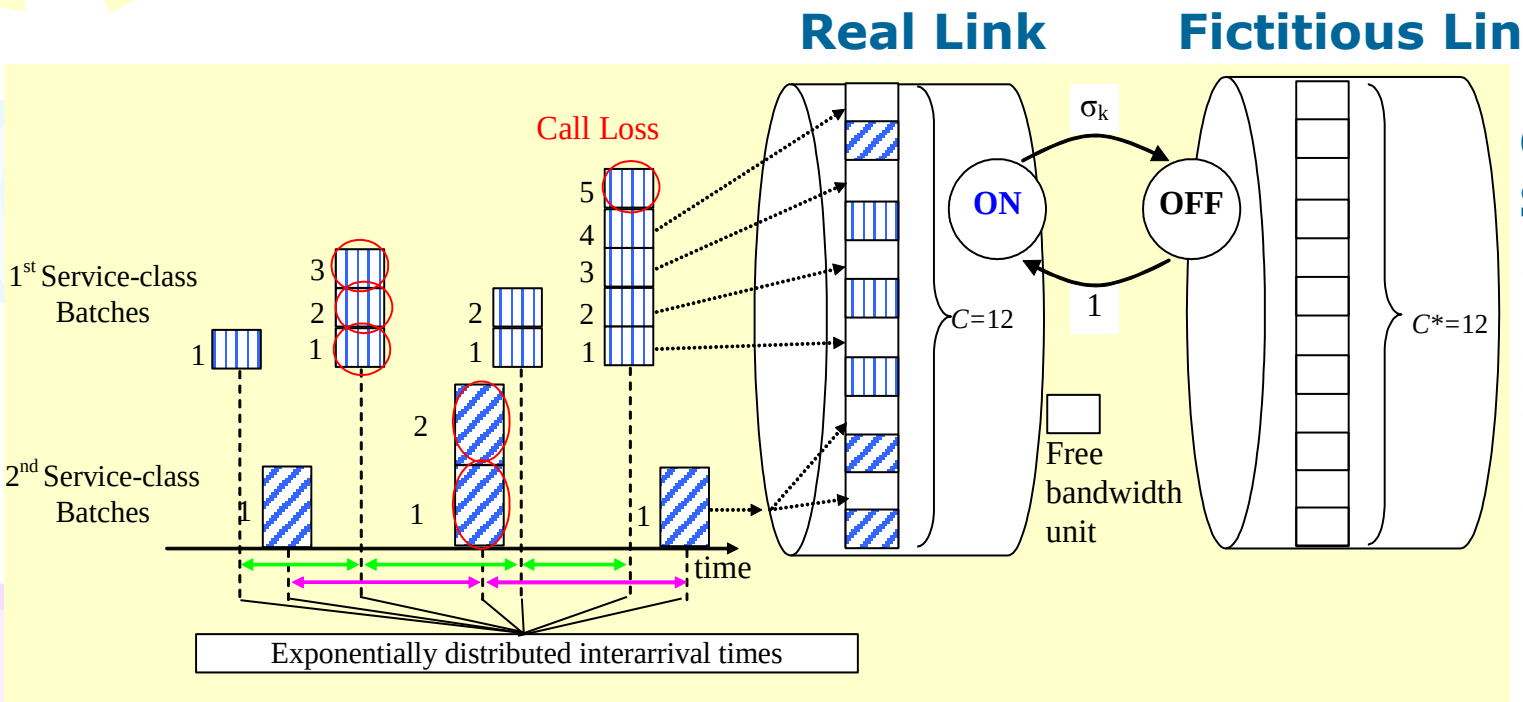

**Batched Poisson arriving calls**

**Fixed bandwidth requirements upon arrival**

**ON-OFF traffic, while in service**

# The Batched Poisson ON-OFF Model (BP-ON-OFF)

**$B_{kr}$ probability that there are r calls in an arriving batch of service-class k.**



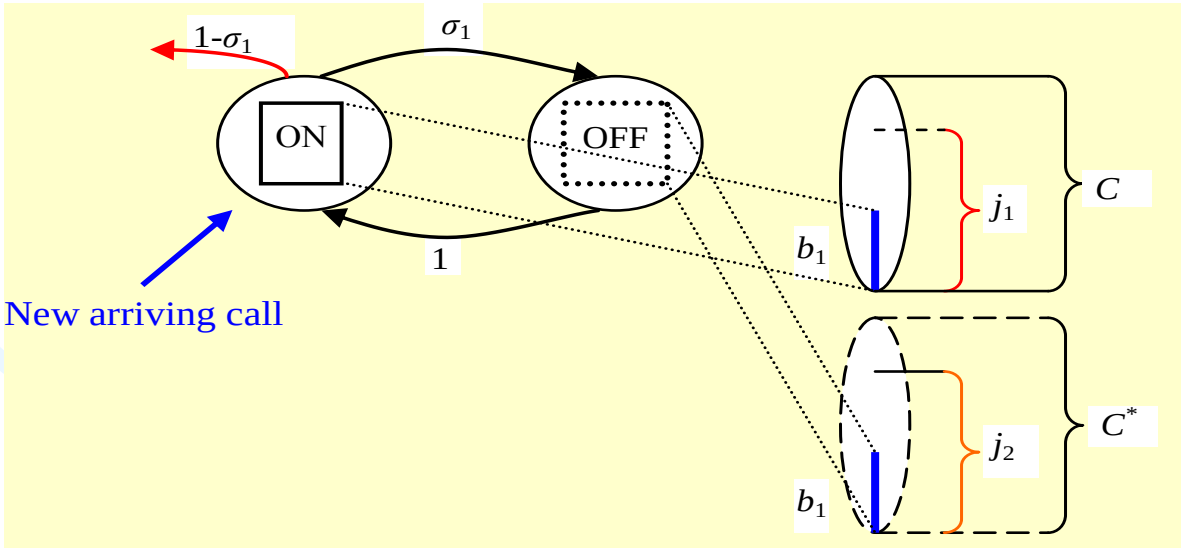

**Complete Sharing Policy**

**Partial Batch Blocking**

# The incorporated ON-OFF model

## The system

- ✓ **Real and Fictitious Link**
- **Fixed Bandwidth Requirement upon Arrival**

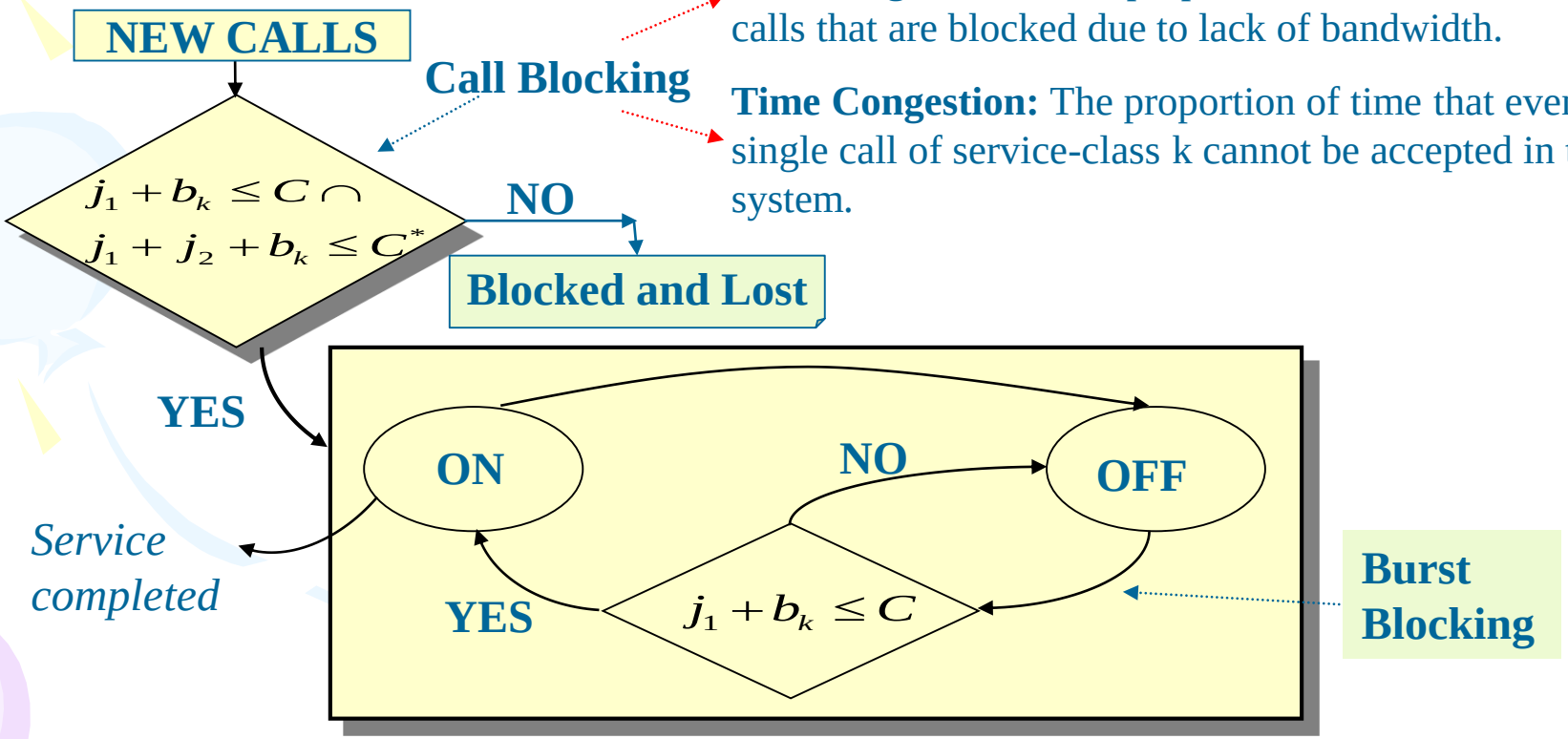



**Real Link**

**Fictitious Link**

# The BP ON-OFF Model – CAC

**Each call is serviced according to the following scheme:**




**Call Congestion:** The proportion of service-class k calls that are blocked due to lack of bandwidth.

**Time Congestion:** The proportion of time that even a single call of service-class k cannot be accepted in the system.

# The analytical BP-ON-OFF Model

## Local Balance does not exist but "Local Flow Balance" does exist

**i = 1 ⇒ state ON**

**i = 2 ⇒ state OFF**

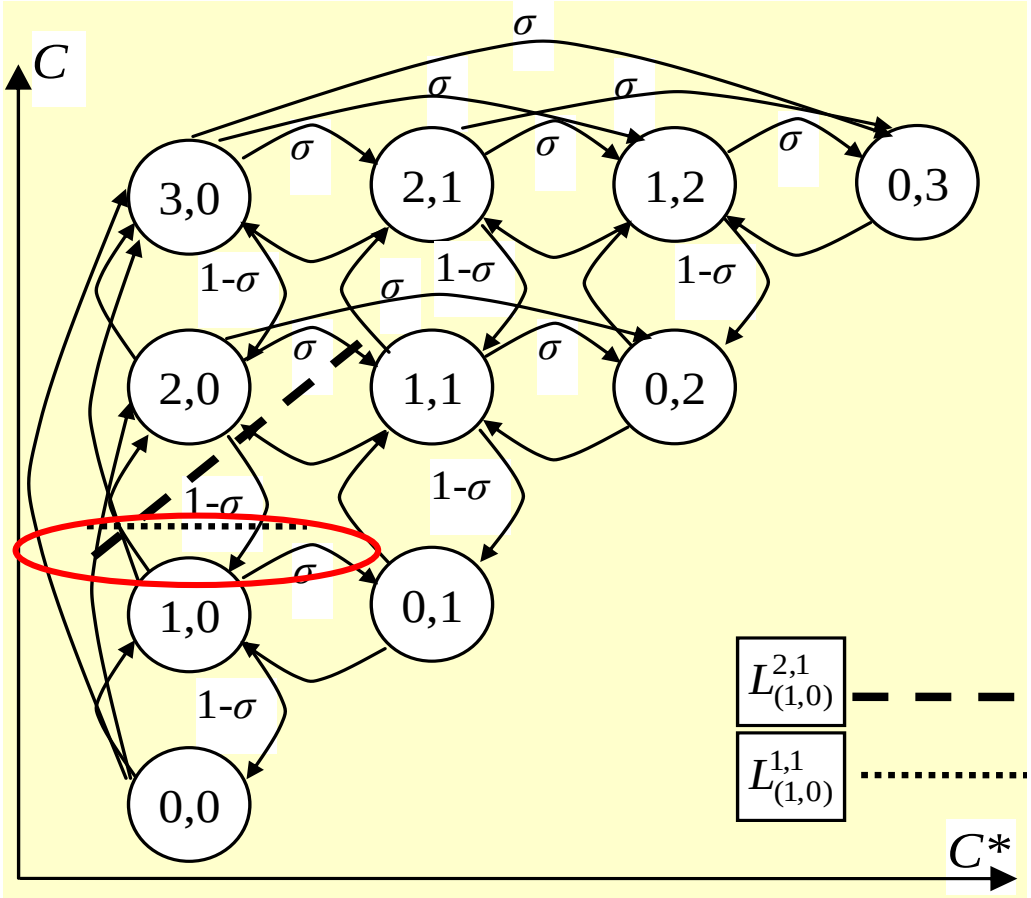
$n^i = (n^i_1, \ldots, n^i_k, \ldots, n^i_K)$

$n^i_{k+l} = (n^i_1, \ldots, n^i_k + l, \ldots, n^i_K)$

$n^i_{k-l} = (n^i_1, \ldots, n^i_k - l, \ldots, n^i_K)$

$$\vec{n}^1_{k+l} = (n^1_{k+l}, n^2) \qquad \vec{n}^1_{k-l} = (n^1_{k-l}, n^2)$$

$$\vec{n}^2_{k+l} = (n^1, n^2_{k+l}) \qquad \vec{n}^2_{k-l} = (n^1, n^2_{k-l})$$




$L^{1,k}_{\vec{n}}$ **the level that separates the state-vector** $\vec{n}$ **from the state** $\vec{n}^1_{k+1}$

$L^{2,k}_{\vec{n}}$ **the level that separates the state-vector** $\vec{n}$ **from the state** $\vec{n}^2_{k+1}$

# The analytical BP-ON-OFF Model (cont.1)

**Flow_up = Flow_down (for each level)**

$$f^{(up)}(L^{1,k}_{\vec{n}}) = \sum_{l=0}^{n_k^1} P(\vec{n}^{\,1}_{k-l})\lambda_k \hat{B}_l^{(k)}$$ **upward probability flow across the level** $L^{1,k}_{\vec{n}}$

$$f^{(down)}(L^{1,k}_{\vec{n}}) = \mu_{1k}(n_k^1+1)(1-\sigma_k)P(\vec{n}^{\,1}_{k+1})$$ **downward probability flow across the level** $L^{1,k}_{\vec{n}}$

$$f^{(up)}(L^{2,k}_{\vec{n}}) = \sum_{l=0}^{n_k^2} P(\vec{n}^{\,2}_{k-l})\lambda_k \sigma_k \hat{B}_l^{(k)}$$ **upward probability flow across the level** $L^{2,k}_{\vec{n}}$

$$f^{(down)}(L^{2,k}_{\vec{n}}) = \mu_{2k}(n_k^2+1)(1-\sigma_k)P(\vec{n}^{\,2}_{k+1})$$ **downward probability flow across the level** $L^{2,k}_{\vec{n}}$

$$\left.\begin{aligned} f^{(up)}(L^{1,k}_{\vec{n}}) &= f^{(down)}(L^{1,k}_{\vec{n}}) \\ f^{(up)}(L^{2,k}_{\vec{n}}) &= f^{(down)}(L^{2,k}_{\vec{n}}) \end{aligned}\right\}$$ **Local Flow Balance equations**

$$\left.\begin{aligned} & f^{(up)}(L^{1,k}_{\vec{n}_{k-1}^{1}}) + f^{(down)}(L^{1,k}_{\vec{n}}) + f^{(up)}(L^{2,k}_{\vec{n}_{k-1}^{2}}) + f^{(down)}(L^{2,k}_{\vec{n}}) = \\ & = f^{(up)}(L^{1,k}_{\vec{n}}) + f^{(down)}(L^{1,k}_{\vec{n}_{k-1}^{1}}) + f^{(up)}(L^{2,k}_{\vec{n}}) + f^{(down)}(L^{2,k}_{\vec{n}_{k-1}^{2}}) \end{aligned}\right\}$$ **Global Balance equation**

# The analytical BP-ON-OFF Model (cont.2)

**Local Flow Balance** ⇨ **Product Form Solution**

$$P(\vec{n}) = \frac{\prod_{i=1}^{2}\prod_{k=1}^{K} P(n_k^i)}{G}$$

$$P(n_k^i) = \begin{cases} \sum_{l=1}^{n_k^i} p_{i,k} \dfrac{P(n_k^i - l)\hat{B}_{l-1}^{(k)}}{n_k^i} & for \quad n_k^i \geq 1 \\ 1 & for \;\; n_k^i = 0 \end{cases}$$

**where** $\hat{B}_l^k = \sum_{r=l+1}^{\infty} B_r^k$ **and** $p_{ik} = \dfrac{e_{ik}}{\mu_{ik}} = \begin{cases} \dfrac{\lambda_k}{(1-\sigma_\kappa)\mu_{1\kappa}} & \text{for} \quad i=1 \\ \dfrac{\lambda_k \sigma_\kappa}{(1-\sigma_\kappa)\mu_{2\kappa}} & \text{for} \quad i=2 \end{cases}$

**complementary batch size distribution**

**utilization of state i**

# The analytical BP-ON-OFF Model (cont.3)

## Link occupancy distribution

Un-normalized

$$q(\vec{j}) = \begin{cases} 1 & for \;\; \vec{j} = 0 \\ \frac{1}{j_s} \sum_{i=1}^{2} \sum_{k=1}^{K} b_{i,k,s} p_{ik} \sum_{l=1}^{\lfloor j_s / b_k \rfloor} \hat{B}_{l-1}^{k} q(\vec{j} - lB_{i,k}) & for \;\; j_1 = 1,\ldots,C \;\; (if \;\; s=1) \;\; or \;\; for \;\; j_2 = 1,\ldots,C^* - j_1 \;\; (if \;\; s=2) \\ 0 & otherwise \end{cases}$$

## Performance measures

**Time Congestion probability**

**accurate**

$$P_{b_k} = \sum_{\{\vec{j} | j_1 + j_2 + b_k > C\}} G^{-1} q(\vec{j})$$

$$G = \sum_{\vec{j} \in \Omega} q(\vec{j})$$

$$\Omega = \left\{ \vec{n} : \sum_{i=1}^{2} \sum_{k=1}^{K} n_k^i b_k \le C \right\}$$

**Call Congestion probability**

**accurate**

$$C_{b_k} = \frac{(p_{1k} + p_{2k}) \hat{B}_k - (\bar{n}_k^1 + \bar{n}_k^2)}{(p_{1k} + p_{2k}) \hat{B}_k}$$

**Burst Blocking probability**

**approximate**

$$P_{bk}^* = \frac{\sum_{(\vec{j} \in \Omega^*)} y_{2k}(\vec{j}) q(\vec{j}) \mu_{2k}}{\sum_{(\vec{j} \in \Omega)} y_{2k}(\vec{j}) q(\vec{j}) \mu_{2k}}$$

$$y_{ik}(\vec{j}) = \frac{p_{i,k} \sum_{l=1}^{\lfloor j_s / b_k \rfloor} \hat{B}_{l-1}^{k} q(\vec{j} - lB_{i,k})}{q(\vec{j})}$$

# BP-ON-OFF Model: Numerical example

**K = 2 service-classes**

**$b_1$= 1, $b_2$= 12 b.u. per call**

**C = C*=60 b.u.**

**The batch size, $s_k$, is given by the geometric distribution, i.e. $P_r(s_k=r)=(1-\beta_k)\beta^{r-1}_k$ . In this example $\beta_1$=0.2, $\beta_2$=0.5.**

**Arrival rate: $\lambda_1$=10, $\lambda_2$=2**

**Call holding time, exponentially distributed:**

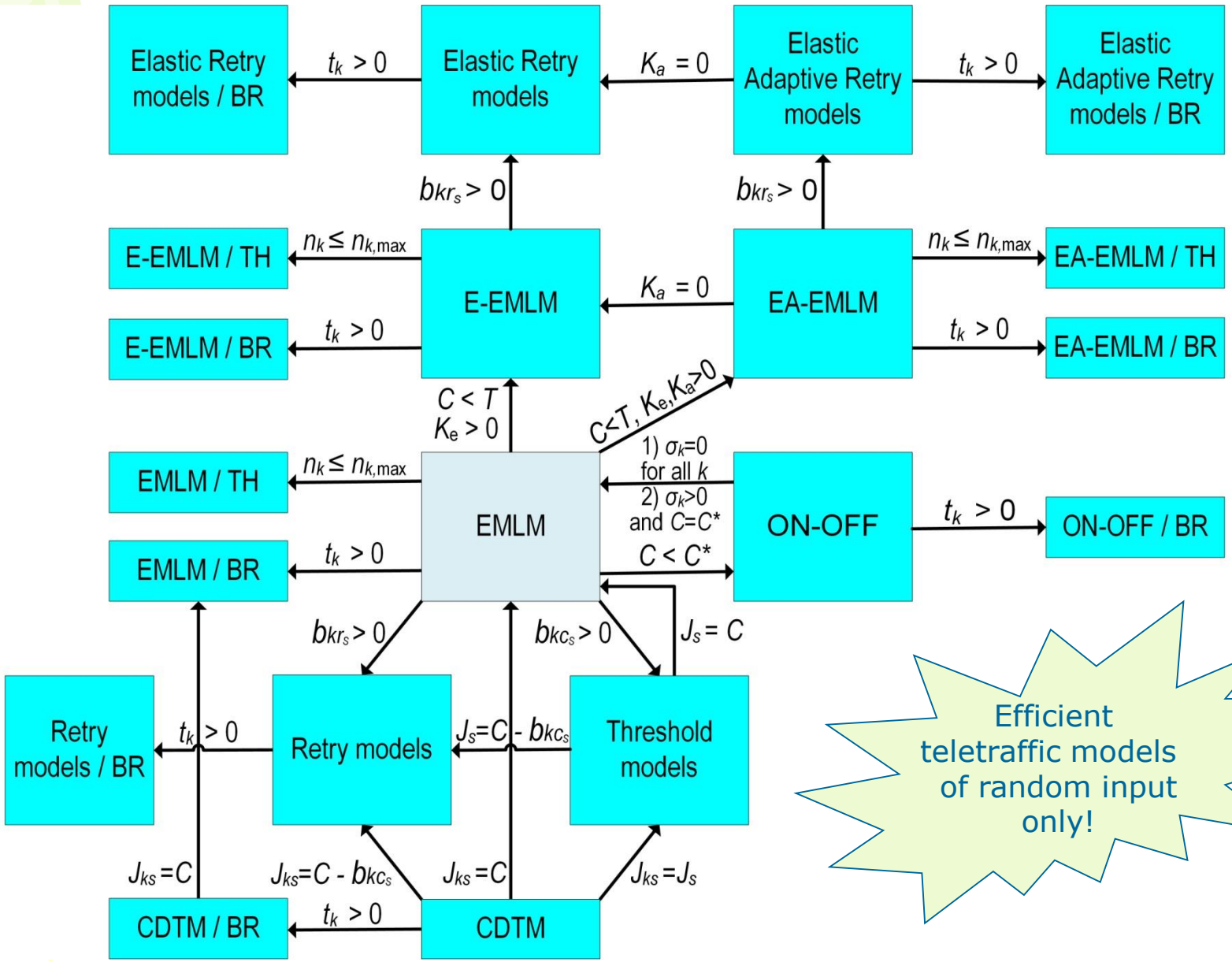
**1st service-class: $\mu^{-1}_{11}$=0.0405 (state ON), $\mu^{-1}_{21}$= 0.01 (state OFF).**

**2nd service-class: $\mu^{-1}_{12}$=0.0405 (state ON), $\mu$-$^{1}_{22}$= 0.01 (state OFF).**

# BP-ON-OFF Model: Numerical example

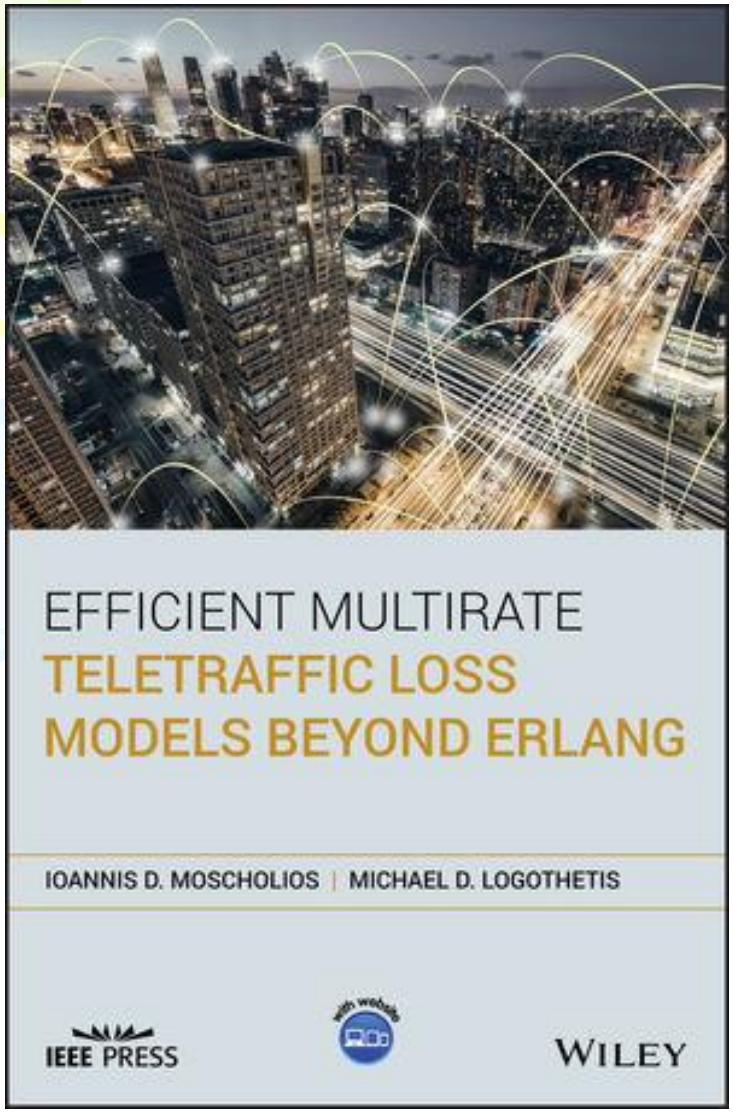
| | Time Congestion (%) | | Simulation results (%) | |
|---|---|---|---|---|
| $\lambda_2$ | 1st class | 2nd class | 1st class | 2nd class |
| 2 | 2.52 | 25.56 | 2.51 ± 0.06 | 25.55 ± 0.23 |
| 1.8 | 2.20 | 22.99 | 2.19 ± 0.07 | 23.02 ± 0.16 |
| 1.6 | 1.88 | 20.32 | 1.86 ± 0.07 | 20.29 ± 0.12 |
| 1.4 | 1.57 | 17.54 | 1.57 ± 0.06 | 17.55 ± 0.14 |
| 1.2 | 1.26 | 14.69 | 1.24 ± 0.03 | 14.65 ± 0.10 |
| 1.0 | 0.97 | 11.79 | 0.99 ± 0.01 | 11.77 ± 0.15 |
| 0.8 | 0.70 | 8.92 | 0.70 ± 0.01 | 8.92 ± 0.18 |

# SUMMARY




Efficient teletraffic models of random input only!

# References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3η έκδοση

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**Thank You !**