Bandwidth Sharing Policies for 4G/5G Networks

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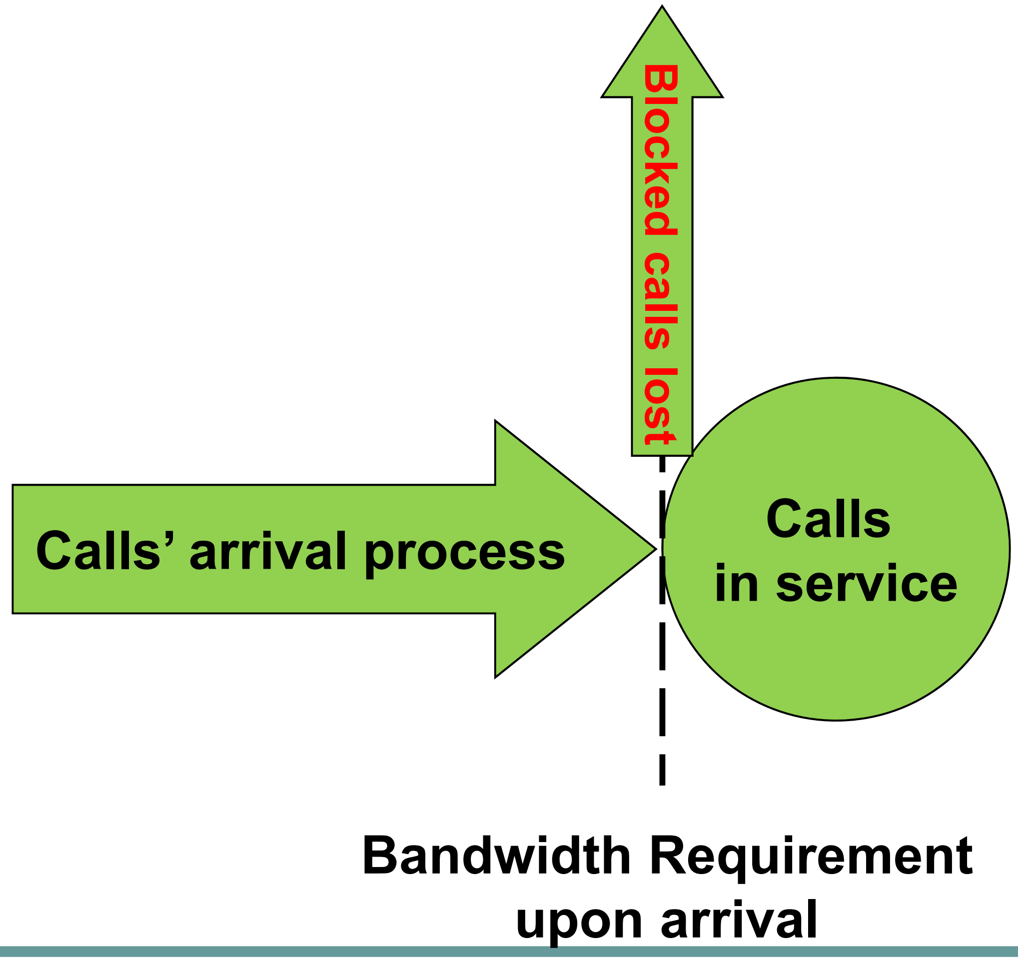
Structure

- Background
- The model
- Bandwidth sharing policies
  - The Complete Sharing (CS) Policy
  - The Bandwidth Reservation (BR) Policy (*Guard Channel Policy*)
  - The Multiple Fractional Channel Reservation (MFCR) Policy
  - The Probabilistic Threshold (PrTH) Policy
- Determination of Call Blocking Probabilities (CBP)
- Application in 4G Networks
- Application in 5G Networks
- Evaluation
- Conclusion

Background (1)

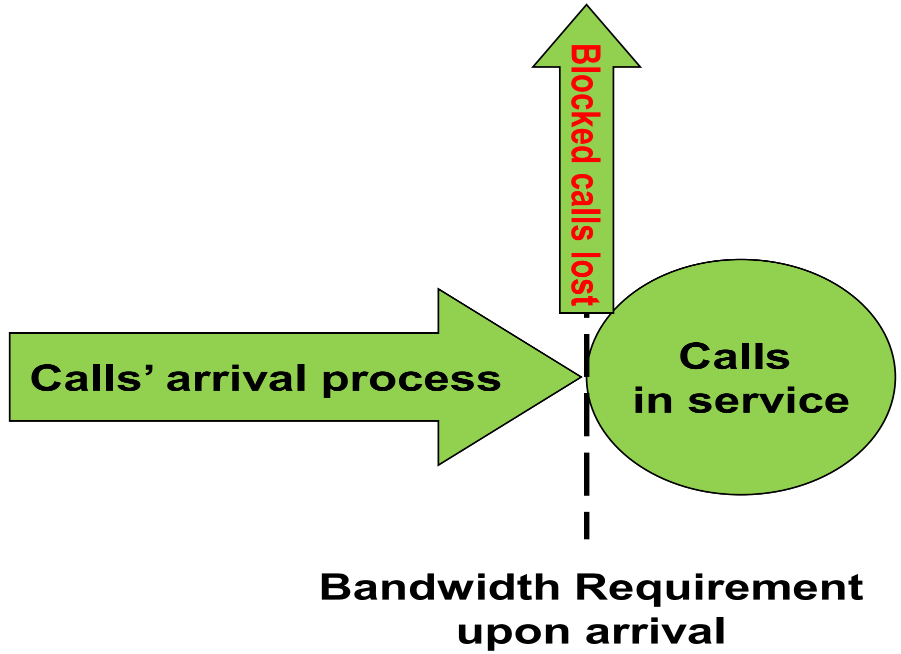
A Loss Service System



Background (2)

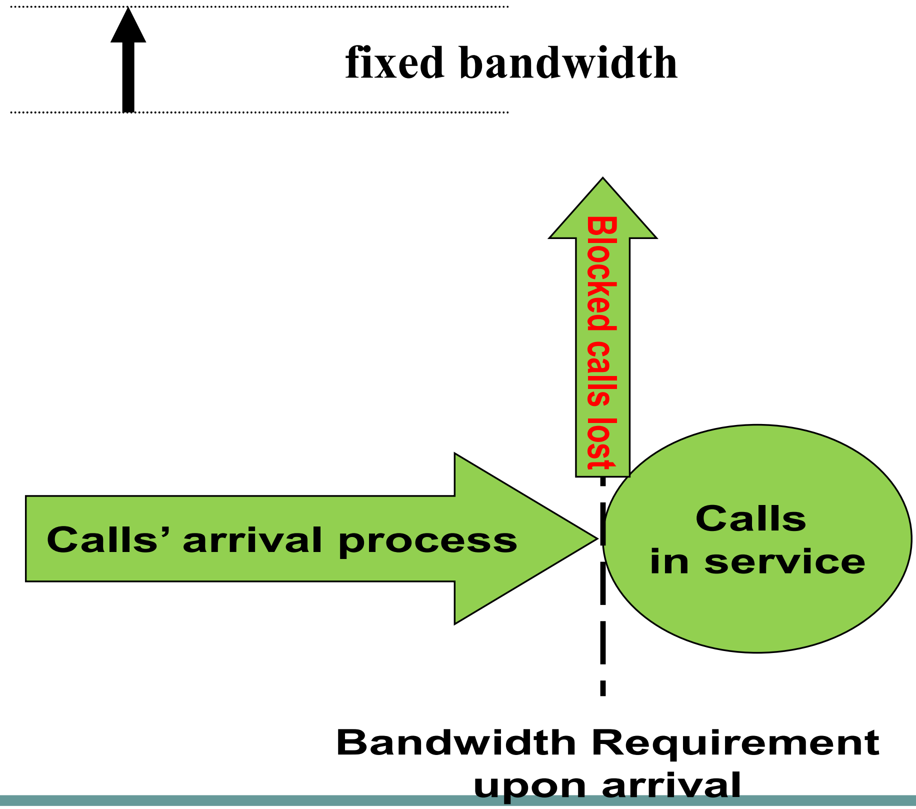
Calls' Arrival Process

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



Background (3)

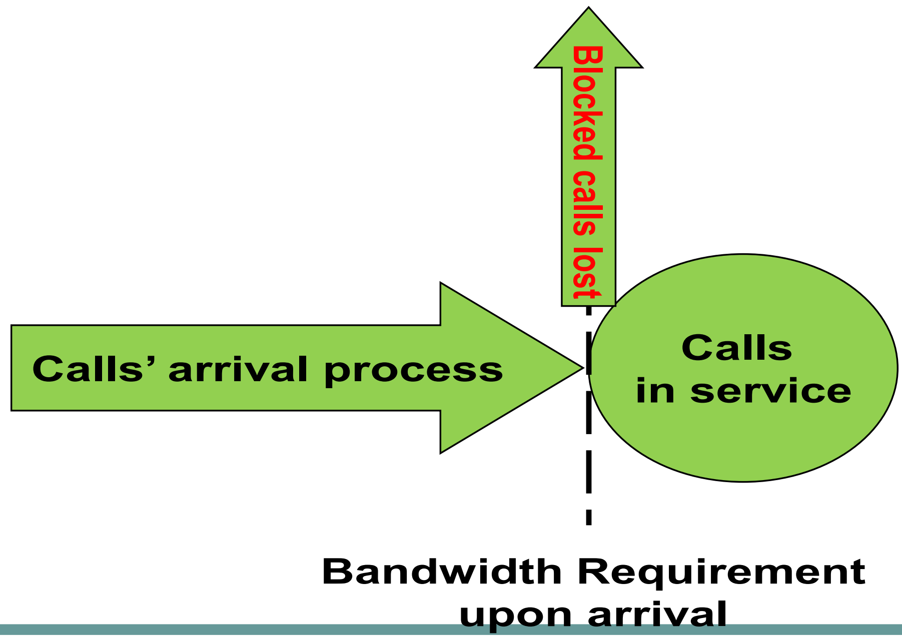
Bandwidth Requirement upon arrival



Background (4)

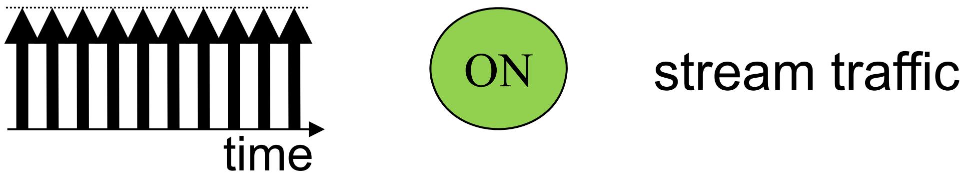
Bandwidth Sharing Policy

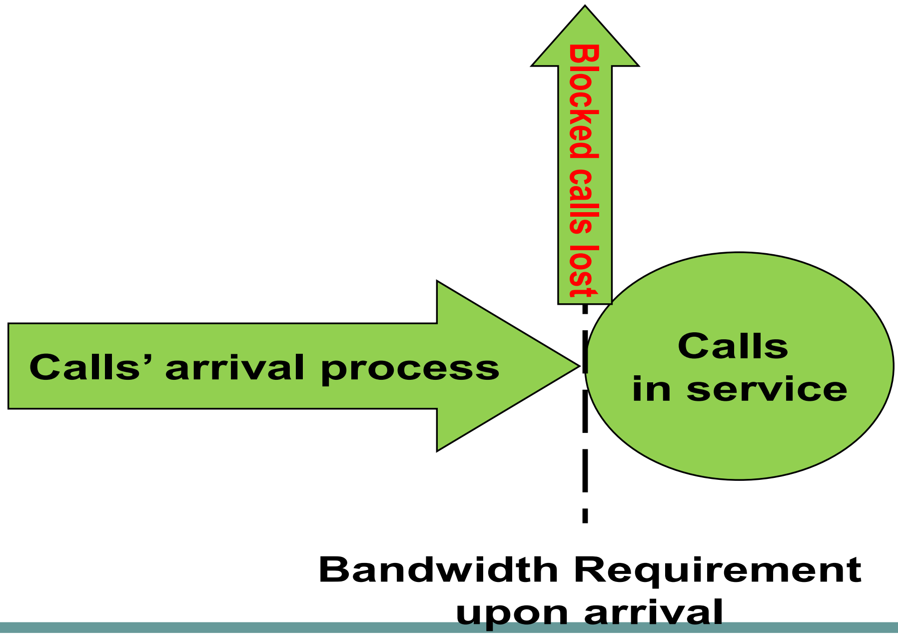
- ✓ **Determines how bandwidth units are shared between calls**
- ✓ **Provides a call admission mechanism that affects Call Blocking Probabilities**



Background (5)

Calls' behavior while in service





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The model

- ✓ A reference cell of fixed capacity in a wireless cellular network
- ✓ The cell accommodates new and handover calls from different service-classes
- ✓ Arriving calls follow a random or quasi-random process
- ✓ Arriving calls have different bandwidth requirements
- ✓ Calls compete for service in the cell under four bandwidth sharing policies (CS, BR, MFCR, PrTH policies)
- ✓ The cell is modeled as a multirate loss system

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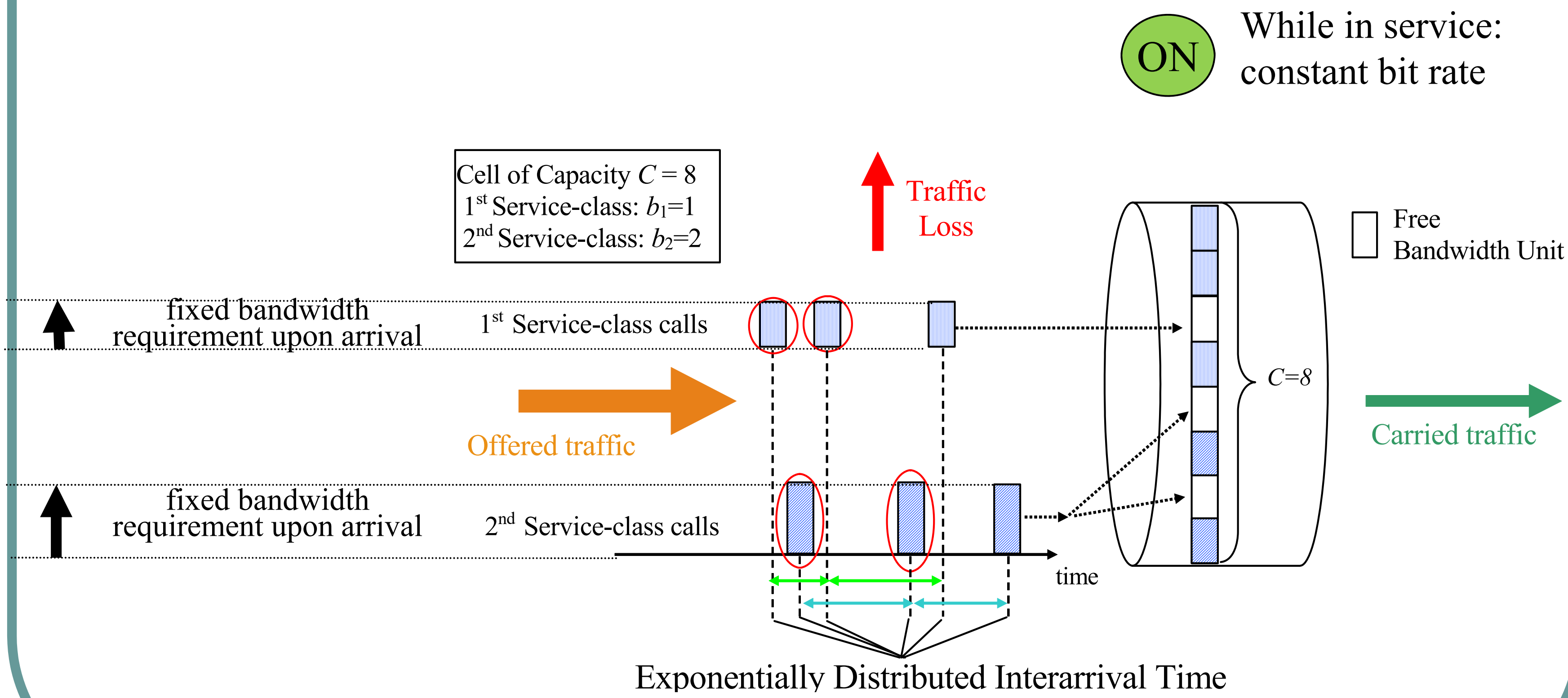
Bandwidth Sharing Policies (1)

The Complete Sharing (CS) Policy (1)

(in a multirate loss system)



Bandwidth Sharing Policies (2)

The Complete Sharing (CS) Policy (2)

(in a multirate loss system)

Admission control cases:

Let *j* be the occupied system's bandwidth (*j* = 0, 1, …, *C*) when a call of service-class *k* arrives in the cell. The call has a bandwidth requirement of b_k b.u. Then:

$$\text{if } C - j \geq b_k \rightarrow \text{the new call is accepted}$$

$$\text{if } C - j < b_k \rightarrow \text{the new call is blocked and lost}$$

Bandwidth Sharing Policies (3)

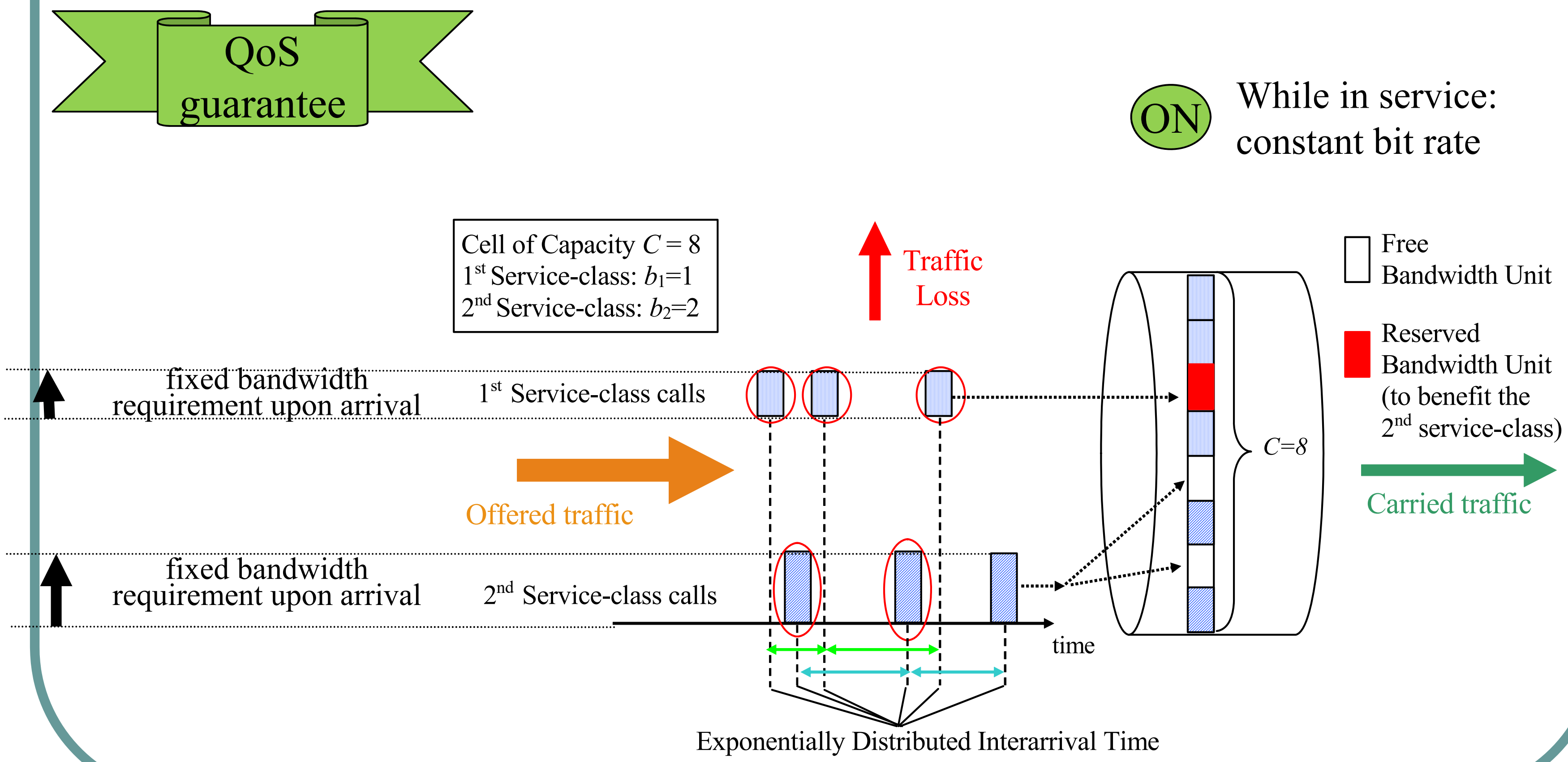
The Complete Sharing (CS) Policy (3)

(in a multirate loss system)

- ✓ The simplest policy BUT
  - ❖ It is unfair to calls with higher bandwidth requirements since it leads to higher CBP
  - ❖ It does not provide different treatment to handover calls, i.e., calls transferred from one cell to another while they are still in progress.

Bandwidth Sharing Policies (4)

The Bandwidth Reservation (BR) Policy (1)



Bandwidth Sharing Policies (5)

The Bandwidth Reservation (BR) Policy (2)

Admission control cases:

Let j be the occupied system's bandwidth (j = 0, 1, …, C) when a call of service-class k arrives in the cell. The call has a bandwidth requirement of b_k b.u. and a BR parameter t_k.

The BR parameter shows the b.u. reserved to benefit calls of all other service-classes apart from k.

Then:

$$\text{if } C - j - t_k \geq b_k \rightarrow \text{the new call is accepted}$$

$$\text{if } C - j - t_k < b_k \rightarrow \text{the new call is blocked and lost}$$

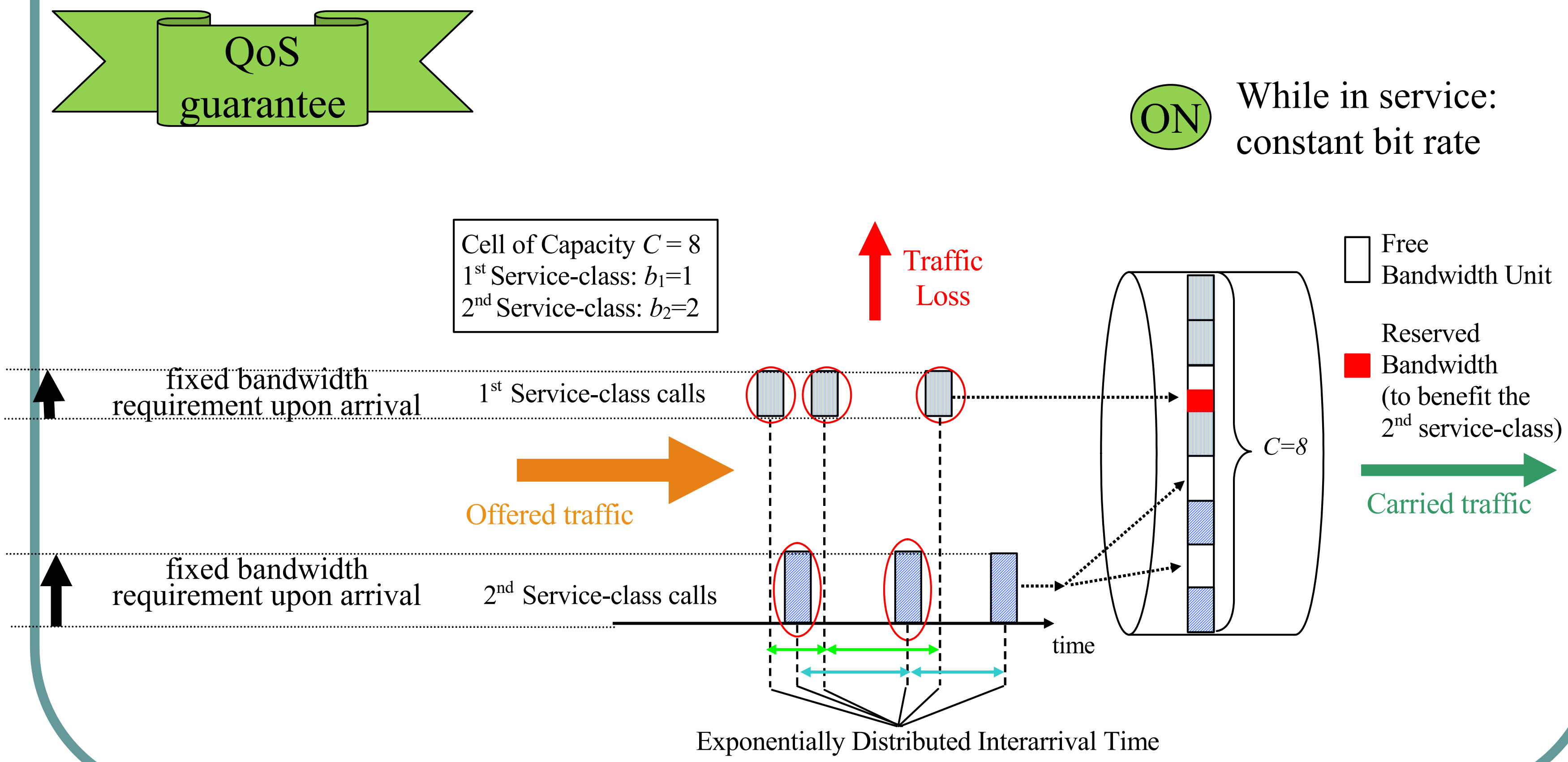
Bandwidth Sharing Policies (6)

The Bandwidth Reservation (BR) Policy (3)

- ✓ It introduces a service priority to benefit high-speed calls
- ✓ It can achieve CBP equalization among calls of different service classes at the expense of substantially increasing the CBP of lower-speed calls.

Bandwidth Sharing Policies (7)

The Multiple Fractional Channel Reservation (MFCR) Policy (1)



Bandwidth Sharing Policies (8)

The Multiple Fractional Channel Reservation (MFCR) Policy (2)

It generalizes the BR policy by allowing the reservation of real (not integer) number of channels.

Note: A channel does not refer to an actual physical or logical communication channel but to a bandwidth (data rate) unit.

Example: A service-class k call has an MFCR parameter of $t_{r,1}$ = 0.4 channels. The reservation of 0.4 channels is achieved by assuming that $\lfloor 0.4 \rfloor + 1 = 1$ channel is reserved with probability $0.4 - \lfloor 0.4 \rfloor = 0.4$ while $\lfloor 0.4 \rfloor = 0$ channels are reserved with probability $1 - (0.4 - \lfloor 0.4 \rfloor) = 0.6$

Bandwidth Sharing Policies (9)

The Multiple Fractional Channel Reservation (MFCR) Policy (3)

Admission control cases:

Let j be the occupied system's bandwidth (j = 0, 1, …, C) when a call of service-class k arrives in the cell. The call has a bandwidth requirement of b_k b.u. and an MFCR parameter $t_{r,k}$. Then:

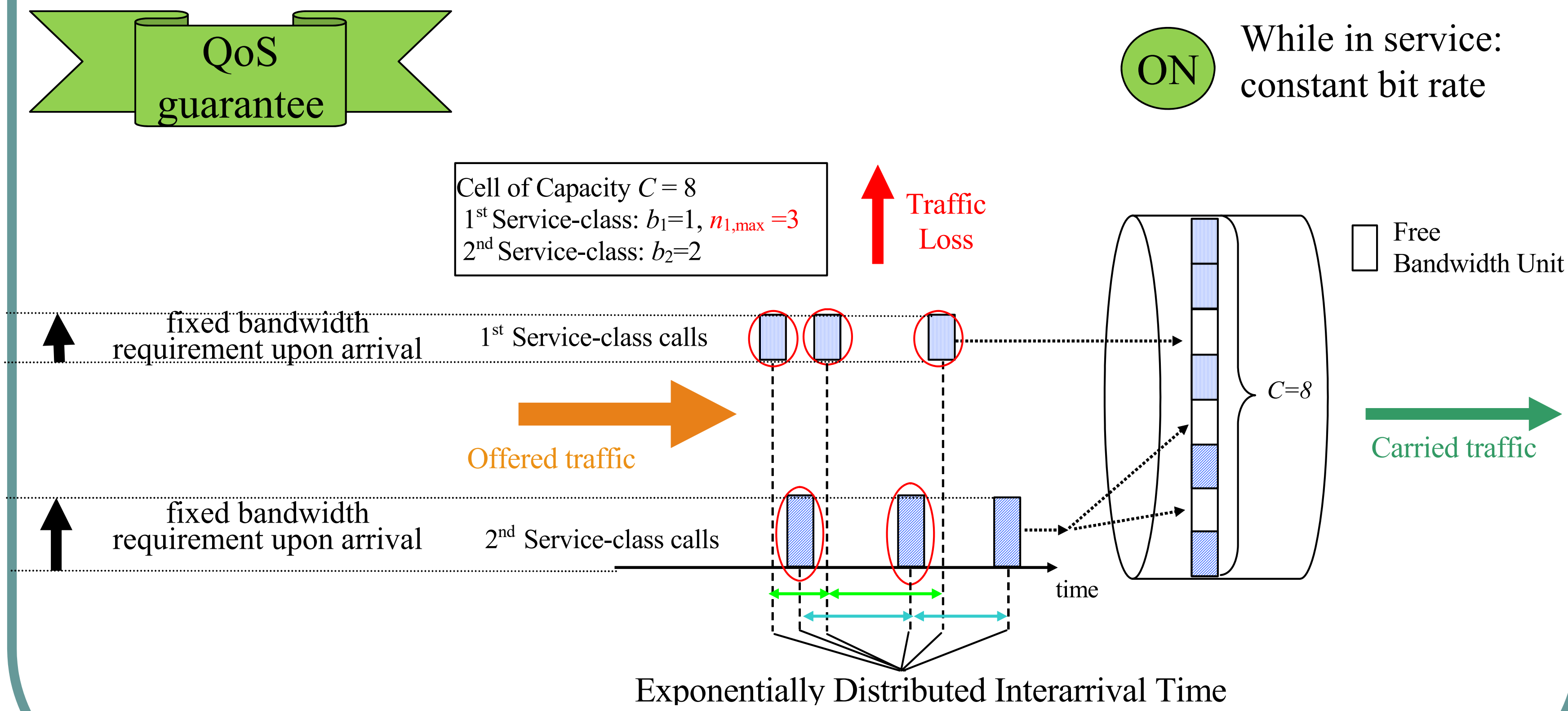
$$if\ C - j - \lfloor t_{r,k} \rfloor > b_k \ \rightarrow the\ new\ call\ is\ accepted$$

$$if\ C - j - \lfloor t_{r,k} \rfloor = b_k \ \rightarrow the\ new\ call\ is\ accepted\ with\ prob.\ 1 - \left(t_{r,k} - \lfloor t_{r,k} \rfloor \right)$$

$$if\ C - j - \lfloor t_{r,k} \rfloor < b_k \ \rightarrow the\ new\ call\ is\ blocked\ and\ lost$$

Bandwidth Sharing Policies (10)

The Probabilistic Threshold Policy (PrTH) Policy (1)



Bandwidth Sharing Policies (11)

The Probabilistic Threshold Policy (PrTH) Policy (2)

- ✓ In the threshold (not probabilistic) policy, the number of in-service calls of a service-class plus the new call must not exceed a threshold (dedicated to the service-class). Otherwise, call blocking occurs even if available bandwidth exists in the system.
- ✓ In the probabilistic TH policy (PrTH policy), call acceptance is permitted above a threshold, with a probability.
- ✓ This probability depends on the service-class, the type of call (new or handover) and the system state.

Bandwidth Sharing Policies (12)

The Probabilistic Threshold Policy (PrTH) Policy (3)

Admission control cases:

Let j be the occupied system's bandwidth (j = 0, 1, …, C) when a call of service-class k arrives in the cell. Let also n_k be the number of in-service calls of service-class k. The call has a bandwidth requirement of b_k b.u. Then:

$$\text{a)}\ \ if\ \ C - j \geq b_k$$

$$\text{a1)}\ if\ \ n_k + 1 \leq n_{k,\max} \rightarrow the\ call\ is\ accepted\ in\ the\ system$$

$$\text{a2)}\ if\ \ n_k + 1 > n_{k,\max} \rightarrow the\ call\ is\ accepted\ in\ the\ system\ with\ prob.\ p_k(n_k)$$

$$or\ blocked\ with\ prob.\ 1 - p_k(n_k)$$

$$\text{b)}\ \ if\ \ C - j < b_k \qquad \rightarrow the\ call\ is\ blocked\ and\ lost$$

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Determination of Call Blocking Probabilities (CBP) (1)

Basic Definitions (1)

C: capacity of the cell in bandwidth units (b.u.)

j: occupied system's bandwidth ($j=0,\dots,C$)

$q(j)$: unnormalized values of the system's occupancy distribution

K: service-classes accommodated in the cell

λ_k: arrival rate of service-class k (k=1,…,K) calls

μ^{-1}_k: service time of service-class k calls (generally distributed)

$\alpha_k = \lambda_k / \mu_k$: offered traffic-load (in erlang)

b_k: required b.u. for service-class k calls

t_k: BR parameter

$t_{r,k}$: MFCR parameter

n_k: number of in-service calls of service-class k

$n_{k,max}$: max. number of in-service calls of service-class k

Determination of Call Blocking Probabilities (CBP) (2)

Basic Definitions (2)

N_k: number of traffic sources of service-class k

v_k: arrival rate per idle source of service-class k (k=1,…,K)

$\alpha_{k,fin} = v_k / \mu_k$: offered traffic-load per idle source (in erlang)

Determination of Call Blocking Probabilities (CBP) (3)

In the CS Policy (assuming Poisson/random arrivals)

The Erlang Multirate Loss Model (EMLM)

Kaufman-Roberts recursion (1981)

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

CBP

$$B_k = \sum_{j=C-b_k+1}^{C} G^{-1} q(j) \quad \text{where} \quad G = \sum_{j=0}^{C} q(j)$$

- J. Kaufman, "Blocking in a shared resource environment", *IEEE Trans. Commun*. vol. 29, no. 10, pp. 1474-1481, Oct. 1981.
- J. Roberts, "A service system with heterogeneous user requirements", Performance of Data Communications systems and their applications, North Holland, pp.423-431, 1981.

Determination of Call Blocking Probabilities (CBP) (4)

In the CS Policy (assuming quasi-random arrivals)

The Engset Multirate Loss Model (EnMLM) (1)

$$q_{fin}(j)=\begin{cases}1, & for\ j=0\\ \frac{1}{j}\sum_{k=1}^{K}(N_k-y_k(j-b_k))a_{k,fin}(j-b_k)b_k q_{fin}(j-b_k), & for\ j=1,...,C\\ 0, & otherwise\end{cases}$$

$$y_k(j)=\begin{cases}\frac{a_k q(j-b_k)}{q(j)} & for\quad j\le C\\ 0 & otherwise\end{cases}$$

Determined via the EMLM

- G. Stamatelos and J. Hayes, “Admission control techniques with application to broadband networks”, Comput. Commun., 17 (9), pp. 663-673, 1994.
- M. Stasiak and M. Glabowski, “A simple approximation of the link model with reservation by a one-dimensional Markov chain”, Performance Evaluation, 41 (2-3), pp.195–208, July 2000.

Determination of Call Blocking Probabilities (CBP) (5)

In the CS Policy (assuming quasi-random arrivals)

The Engset Multirate Loss Model (EnMLM) (2)

Time Congestion Probabilities (for CBP of service-class *k*, consider N_k-1 sources)

$$B_k = \sum_{j=C-b_k+1}^{C} G^{-1} q_{fin}(j) \quad \text{where} \quad G = \sum_{j=0}^{C} q_{fin}(j)$$

For $K = 1 \rightarrow$ $$P_{b1} = \frac{\binom{N}{C}(\alpha_1)^C}{\sum_{i=0}^{C}\binom{N}{i}(\alpha_1)^i}$$ Engset formula (1918)

For $N_k \rightarrow \infty$, $q(j)$ results in Kaufman/Roberts recursion (EMLM)

Determination of Call Blocking Probabilities (CBP) (6)

In the BR Policy (assuming Poisson/random arrivals)

The Erlang Multirate Loss Model under BR (EMLM/BR)

Roberts recursion (1983)

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

$$a_k(j - b_k) = \begin{cases} a_k & for \ \ j \leq C - t_k \\ 0 & otherwise \end{cases}$$

CBP

$$B_k = \sum_{j=C-b_k-t_k+1}^{C} G^{-1} q(j) \quad \text{where} \quad G = \sum_{j=0}^{C} q(j)$$

- J. Roberts, “Teletraffic models for the Telecom 1 Integrated Services Network”, Proc. 10th ITC, paper 1.1-2, Montreal 1983.

Determination of Call Blocking Probabilities (CBP) (7)

In the BR Policy (assuming quasi-random arrivals)

The Engset Multirate Loss Model under BR (EnMLM/BR) (1)

$$q_{fin}(j)=\begin{cases}1, & for\ j=0\\ \frac{1}{j}\sum_{k=1}^{K}(N_k-y_k(j-b_k))a_{k,fin}(j-b_k)b_k q_{fin}(j-b_k), & for\ j=1,...,C\\ 0, & otherwise\end{cases}$$

$$a_{k,fin}(j-b_k)=\begin{cases}a_{k,fin} & for\ \ j\le C-t_k\\ 0 & otherwise\end{cases}$$

$$y_k(j)=\begin{cases}\frac{a_k q(j-b_k)}{q(j)} & for\ \ j\le C-t_k\\ 0 & otherwise\end{cases}$$

Determined via the EMLM/BR

Determination of Call Blocking Probabilities (CBP) (8)

In the BR Policy (assuming quasi-random arrivals)

The Engset Multirate Loss Model under BR (EnMLM/BR) (2)

Time Congestion Probabilities (for CBP of service-class *k*, consider N_k-1 sources)

$$B_k = \sum_{j=C-b_k-t_k+1}^{C} G^{-1} q_{fin}(j) \quad \text{where} \quad G = \sum_{j=0}^{C} q_{fin}(j)$$

- M. Glabowski and M. Stasiak, "An approximate model of the full-availability group with multi-rate traffic and a finite source population", Proc. of 12th MMB&PGTS, Dresden, Germany, Sept. 2004.
- I. Moscholios and M. Logothetis, "Engset Multirate State-Dependent Loss Models with QoS Guarantee", International Journal of Communications Systems, Vol. 19, Issue 1, pp. 67-93, Feb. 2006.

Determination of Call Blocking Probabilities (CBP) (9)

In the MFCR Policy (assuming Poisson/random arrivals)

The MFCR- Random model (MFCR-R)

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

$$a_k(j\text{-}b_k) = \begin{cases} a_k \ \ for \ \ j < C - \lfloor t_{r,k} \rfloor \\ \left(1-\left(t_{r,k} - \lfloor t_{r,k} \rfloor\right)\right) a_k \ \ for \ \ j = C - \lfloor t_{r,k} \rfloor \\ 0 \ \ for \ \ j > C - \lfloor t_{r,k} \rfloor \end{cases}$$

CBP

$$B_k = \sum_{j=C-b_k-\lfloor t_{r,k} \rfloor+1}^{C} G^{-1} q(j) + \left(t_{r,k} - \lfloor t_{r,k} \rfloor\right) G^{-1} q\left(C - b_k - \lfloor t_{r,k} \rfloor\right)$$

F. Cruz-Pérez, J. Vázquez-Ávila and L. Ortigoza-Guerrero, “Recurrent formulas for the multiple fractional channel reservation strategy in multi-service mobile cellular networks”, IEEE Commun. Letters, 8 (10), pp. 629-631, Oct. 2004.

Determination of Call Blocking Probabilities (CBP) (10)

In the MFCR Policy (assuming quasi-random arrivals)

The MFCR- Quasi random model (MFCR-Q) (1)

$$q_{fin}(j)=\begin{cases}1, & for\ j=0\\ \frac{1}{j}\sum_{k=1}^{K}(N_k-y_k(j-b_k))a_{k,fin}(j-b_k)b_k q_{fin}(j-b_k), & for\ j=1,\dots,C\\ 0, & otherwise\end{cases}$$

$$y_k(j)=\begin{cases}\frac{a_k q(j-b_k)}{q(j)} & for\ j<C-\lfloor t_{r,k}\rfloor\\ \frac{\left(1-\left(t_{r,k}-\lfloor t_{r,k}\rfloor\right)\right)a_k q(j-b_k)}{q(j)} & for\ j=C-\lfloor t_{r,k}\rfloor\\ 0 & for\ j>C-\lfloor t_{r,k}\rfloor\end{cases}$$

$$a_{k,fin}(j\text{-}b_k)=\begin{cases}a_{k,fin} & for\ j<C-\lfloor t_{r,k}\rfloor\\ \left(1-\left(t_{r,k}-\lfloor t_{r,k}\rfloor\right)\right)a_{k,fin} & for\ j=C-\lfloor t_{r,k}\rfloor\\ 0 & for\ j>C-\lfloor t_{r,k}\rfloor\end{cases}$$

Determined via the MFCR-R

Determination of Call Blocking Probabilities (CBP) (11)

In the MFCR Policy (assuming quasi-random arrivals)

The MFCR- Quasi random model (MFCR-Q) (2)

Time Congestion Probabilities (for CBP of service-class *k,* consider N_k-1 sources)

$$B_k = \sum_{j=C-b_k-\lfloor t_{r,k} \rfloor+1}^{C} G^{-1} q_{fin}(j) + \left(t_{r,k} - \lfloor t_{r,k} \rfloor\right) G^{-1} q_{fin}\left(C - b_k - \lfloor t_{r,k} \rfloor\right)$$

I. D. Moscholios, V. G. Vassilakis, M. D. Logothetis and A. C. Boucouvalas, "State-dependent Bandwidth Sharing Policies for Wireless Multirate Loss Networks", *IEEE Transactions on Wireless Communications*, vol. 16, issue 8, pp. 5481-5497, August 2017.

Determination of Call Blocking Probabilities (CBP) (12)

In the PrTH Policy (assuming Poisson/random arrivals)

The PrTH Random model (PrTH-R) (1)

A 3-step convolution algorithm for the determination of *q*(*j*)'s

Step 1: Determine $q_k(j)$ of each service-class k in the cell

$$q_k(j) = \begin{cases} q_k(0)\dfrac{a_k^i}{i!} & , for\ 1 \le i \le n_{k,\max}\ and\ \ j = ib_k \\ q_k(0)\dfrac{\prod_{x=n_{k,\max}}^{i-1} p_k(x) a_k^i}{i!} & , for\ n_{k,\max} < i \le \lfloor C/b_k \rfloor and\ \ j = ib_k \\ 0 & , otherwise \end{cases}$$

Determination of Call Blocking Probabilities (CBP) (13)

In the PrTH Policy (assuming Poisson/random arrivals)

The PrTH Random model (PrTH-R) (2)

Step 2: Determine the aggregated $Q_{(-k)}$ (successive convolution of all service-classes)

$$Q_{(-k)} = q_1 * q_2 * \ldots * q_{k-1} * q_{k+1} * \ldots * q_K$$

Note: The convolution operation between two service-classes *k* and *r* is determined as:

$$q_k * q_r = \left\{ q_k(0) q_r(0), \sum_{x=0}^{1} q_k(x) q_r(1-x), \ldots, \sum_{x=0}^{C} q_k(x) q_r(C-x) \right\}$$

Determination of Call Blocking Probabilities (CBP) (14)

In the PrTH Policy (assuming Poisson/random arrivals)

The PrTH Random model (PrTH-R) (3)

Step 3: CBP of service-class *k*

$$B_k = \sum_{j=C-b_k+1}^{C} q(j) + \sum_{x=n_{k,\max} b_k}^{C-b_k} (1 - p_k(x)) q_k(x) \sum_{y=x}^{C-b_k} Q_{(-k)}(C - b_k - y)$$

$$q(j) = \left(\sum_{x=0}^{j} Q_{(-k)}(x) q_k(j-x) \right) / G, \quad j = 1, \ldots, C$$

$$q(0) = Q_{(-k)}(0) q_k(0) / G$$

I. D. Moscholios, V. G. Vassilakis, M. D. Logothetis and A. C. Boucouvalas, "A Probabilistic Threshold-based Bandwidth Sharing Policy for Wireless Multirate Loss Networks", *IEEE Wireless Commun. Letters*, vol. 5, issue 3, pp 304-307, June 2016.

Determination of Call Blocking Probabilities (CBP) (15)

In the PrTH Policy (assuming quasi-random arrivals)

The PrTH Quasi-random model (PrTH-Q) (1)

A 3-step convolution algorithm for the determination of *q*(*j*)'s

Step 1: Determine $q_k(j)$ of each service-class k in the cell

$$q_k(j) = \left\langle \begin{array}{l} q_k(0)\binom{N_k}{i} a_{k,fin}^{i} \quad , for\ 1 \le i \le n_k^{*}\ and\ \ j = ib_k \\ q_k(0)\binom{N_k}{i} \prod_{x=n_k^{*}}^{i-1} p_k(x) a_{k,fin}^{i} \quad , for\ \ n_k^{*} < i \le \lfloor C / b_k \rfloor and\ \ j = ib_k \\ 0 \quad ,\ otherwise \end{array} \right\rangle$$

Determination of Call Blocking Probabilities (CBP) (16)

In the PrTH Policy (assuming quasi-random arrivals)

The PrTH Quasi-random model (PrTH-Q) (2)

Step 2: Determine the aggregated $Q_{(-k)}$ (successive convolution of all service-classes)

$$Q_{(-k)} = q_1 * q_2 * \ldots * q_{k-1} * q_{k+1} * \ldots * q_K$$

Note: The convolution operation between two service-classes *k* and *r* is determined as:

$$q_k * q_r = \left\{ q_k(0) q_r(0), \sum_{x=0}^{1} q_k(x) q_r(1-x), \ldots, \sum_{x=0}^{C} q_k(x) q_r(C-x) \right\}$$

Determination of Call Blocking Probabilities (CBP) (17)

In the PrTH Policy (assuming quasi-random arrivals)

The PrTH Quasi-random model (PrTH-Q) (3)

Step 3: Time Congestion probabilities of service-class *k*

$$B_k = \sum_{j=C-b_k+1}^{C} q(j) + \sum_{x=n_{k,\max}b_k}^{C-b_k} (1-p_k(x))q_k(x)\sum_{y=x}^{C-b_k} Q_{(-k)}(C-b_k-y)$$

$$q(j) = \left(\sum_{x=0}^{j} Q_{(-k)}(x)q_k(j-x)\right) / G, \quad j = 1,\ldots,C$$

$$q(0) = Q_{(-k)}(0)q_k(0) / G$$

I. D. Moscholios, V. G. Vassilakis, M. D. Logothetis and A. C. Boucouvalas, “State-dependent Bandwidth Sharing Policies for Wireless Multirate Loss Networks”, *IEEE Transactions on Wireless Communications*, vol. 16, issue 8, pp. 5481-5497, August 2017.

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Application in 4G Networks (1)

Definitions – Assumptions (1)

Consider the downlink of an OFDM-based cell that has M subcarriers.

Let

R: the average data rate per subcarrier

P: the available power in the cell

B: the system's bandwidth.

Let the entire range of channel gains or signal to noise ratios per unit power be partitioned into K consecutive (but non-overlapping) intervals and denote as γ_k, k=1,…,K the average channel gain of the kth interval.

Considering L subcarrier requirements and K average channel gains, there are LK service-classes.

Application in 4G Networks (2)

Definitions – Assumptions (2)

A newly arriving service-class (k,l) call (k=1,…,K and l=1,…,L) requires b_l subcarriers in order to be accepted in the cell (i.e., the call has a data rate requirement $b_l R$) and has an average channel gain γ_k.

If these subcarriers are not available, the call is blocked and lost (CS policy). Otherwise, the call remains in the cell for a generally distributed service time with mean μ^{-1}.

To calculate the power p_k required to achieve the data rate R of a subcarrier assigned to a call whose average channel gain is γ_k we use the Shannon theorem:

$$R = (B/M)\log_2(1+\gamma_k p_k)$$

Application in 4G Networks (3)

Definitions – Assumptions (3)

Assuming that calls follow a Poisson process with rate λ_{kl} and that n_{kl} is the number of in-service calls of service-class (k,l) then we have a multirate loss model with a product form solution for the steady-state probabilities $\pi(\boldsymbol{n})$

$$\pi(\mathbf{n}) = G^{-1}\left(\prod_{k=1}^{K}\prod_{l=1}^{L} p_{kl}^{n_{kl}} / n_{kl}!\right)$$

$$\mathbf{n} = (n_{11},\ldots,n_{k1},\ldots,n_{K1},\ldots,n_{1L},\ldots,n_{kL},\ldots,n_{KL})$$

$$G = \sum_{\mathbf{n}\in\Omega}\left(\prod_{k=1}^{K}\prod_{l=1}^{L} p_{kl}^{n_{kl}} / n_{kl}!\right) \qquad p_{kl} = \lambda_{kl} / \mu$$

$$\Omega = \left\{ n : 0 \le \sum_{k=1}^{K}\sum_{l=1}^{L} n_{kl} b_l \le M,\ 0 \le \sum_{k=1}^{K}\sum_{l=1}^{L} p_k n_{kl} b_l \le P \right\}$$

C. Paik and Y. Suh, "Generalized queueing model for call blocking probability and resource utilization in OFDM wireless networks", IEEE Commun. Letters, vol. 15, no. 7, pp. 767-769, July 2011.

Application in 4G Networks (4)

Definitions – Assumptions (4)

The derivation of the PFS requires that P and p_k are integers (which is generally not true).

This can be achieved by multiplying both P and p_k by a constant in order to have an equivalent representation of the constraint

$$0 \leq \sum_{k=1}^{K} \sum_{l=1}^{L} p'_k n_{kl} b_l \leq P'$$

integers

Application in 4G Networks (5)

A recursive formula for the calculation of *q*(*j*₁, *j*₂) in the case of the CS policy

$$q(j_1, j_2) = \begin{cases} 1, & \text{for } j_1 = j_2 = 0 \\ \frac{1}{j_1} \sum_{k=1}^{K} \sum_{l=1}^{L} p_{kl} b_l q(j_1 - b_l, j_2 - p_k b_l), & \text{for } j_1 = 1, \dots, M \text{ and } j_2 = 1, \dots, P \end{cases}$$

CBP

$$B(k,l) = \sum_{\{(j_1 + b_l > M) \cup (j_2 + p_k b_l > P)\}} G^{-1} q(j_1, j_2)$$

I. D. Moscholios, V. G. Vassilakis, M. D. Logothetis and A. C. Boucouvalas, "State-dependent Bandwidth Sharing Policies for Wireless Multirate Loss Networks", *IEEE Transactions on Wireless Communications*, vol. 16, issue 8, pp. 5481-5497, August 2017.

Structure

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- Application in 5G Networks
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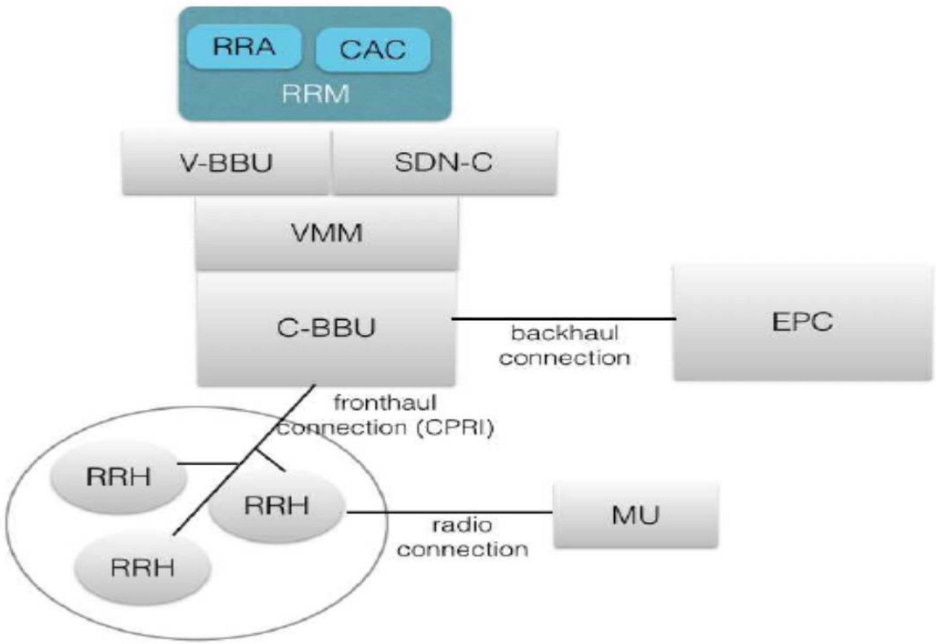
Application in 5G Networks (1)

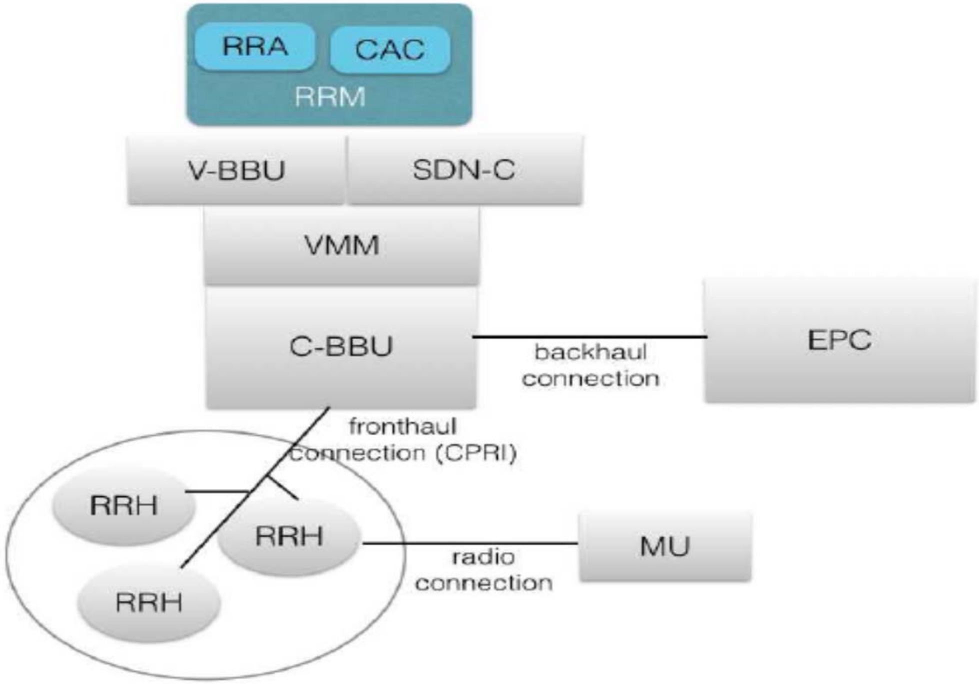
The considered reference architecture which is appropriate for the application of the previous multirate loss models is presented below.

This is in line with the Cloud RAN (C-RAN) architecture, although it can also support a more distributed, Mobile Edge Computing (MEC)-like functionality, by incorporating, e.g., the Self-Organizing (SON) features.



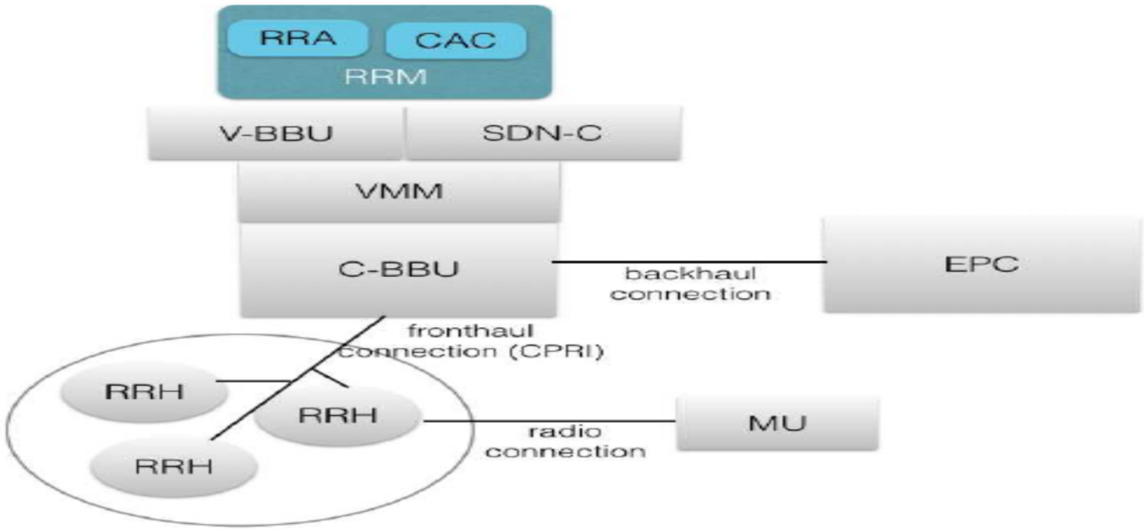
At the RAN level,
the architecture includes an SDN controller (SDN-C) and a virtual machine monitor (VMM) to enable NFV

Application in 5G Networks (2)



Three main parts are distinguished: a pool of remote radio heads (RRHs), a pool of baseband units (BBUs), and the evolved packet core (EPC). The RRHs are connected to the BBUs via the common public radio interface (CPRI) with a high-capacity fronthaul.

Application in 5G Networks (3)



The BBUs form a centralized pool of data center resources (C-BBU). The C-BBU is connected to the EPC via the backhaul connection. To benefit from NFV, we consider virtualized BBU resources (V-BBU) where the BBU functionality and services have been abstracted from the underlying infrastructure and virtualized in the form of virtual network functions (VNFs).

Among the BBU functions that could be virtualized in the form of a VNF, we focus on the RRM, which is responsible for CAC and radio resource allocation (RRA). The CS, BR, PrTH and MFCR policies could be implemented at the RRM level and enable sharing of V-BBU resources among the RRHs.

Application in 5G Networks (4)

An analytical framework for single cluster C-RAN

We adopt the model of [1] and present the analysis for the case where all RRHs in the C-RAN form a single cluster. The analysis for the multi-cluster case is similar and is proposed in [2]. In both [1], [2], the C-RAN accommodates Poisson arriving calls of a single service-class under the CS policy.

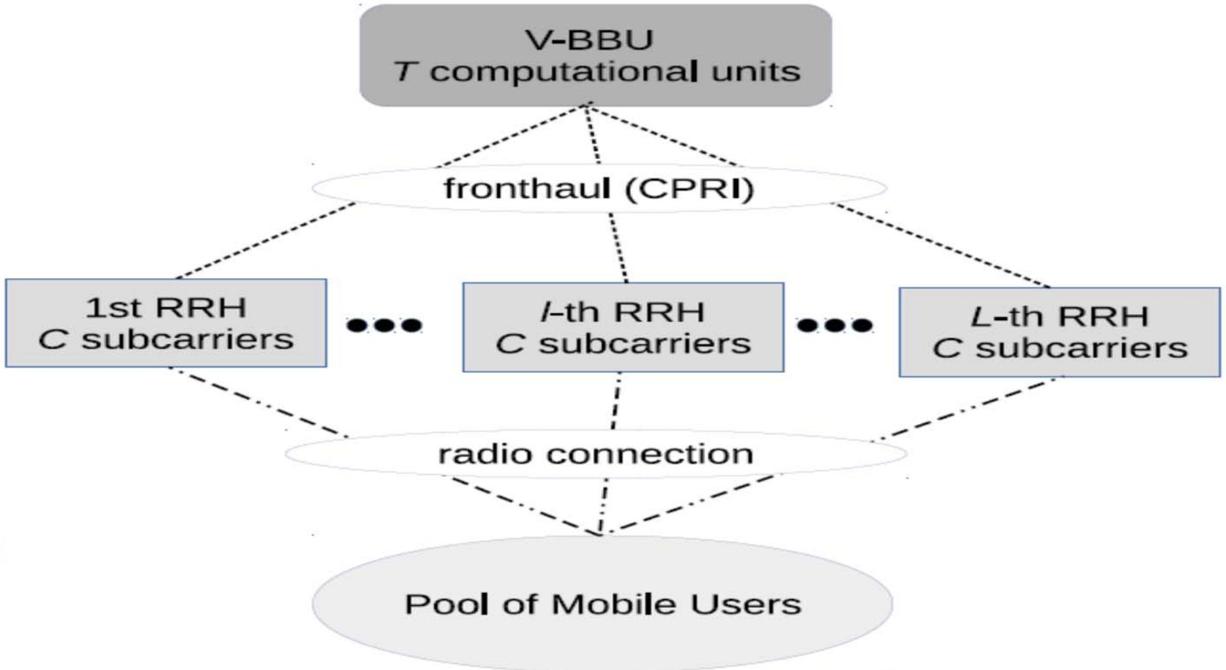
[1] J. Liu, S. Zhou, J. Gong, Z. Niu and S. Xu, "On the statistical multiplexing gain of virtual base station pools," Proc. IEEE Globecom, Austin, TX, Dec. 2014.
[2] J. Liu, S. Zhou, J. Gong, Z. Niu and S. Xu, "Statistical multiplexing gain analysis of heterogeneous virtual base station pools in cloud radio access networks," IEEE Trans. Wireless Commun., vol. 15, no. 8, pp.5681-5694, Aug. 2016.

Application in 5G Networks (5)

Consider the C-RAN model of the Fig where the RRHs are separated from the V-BBU, which performs the centralized baseband processing (of accepted calls).

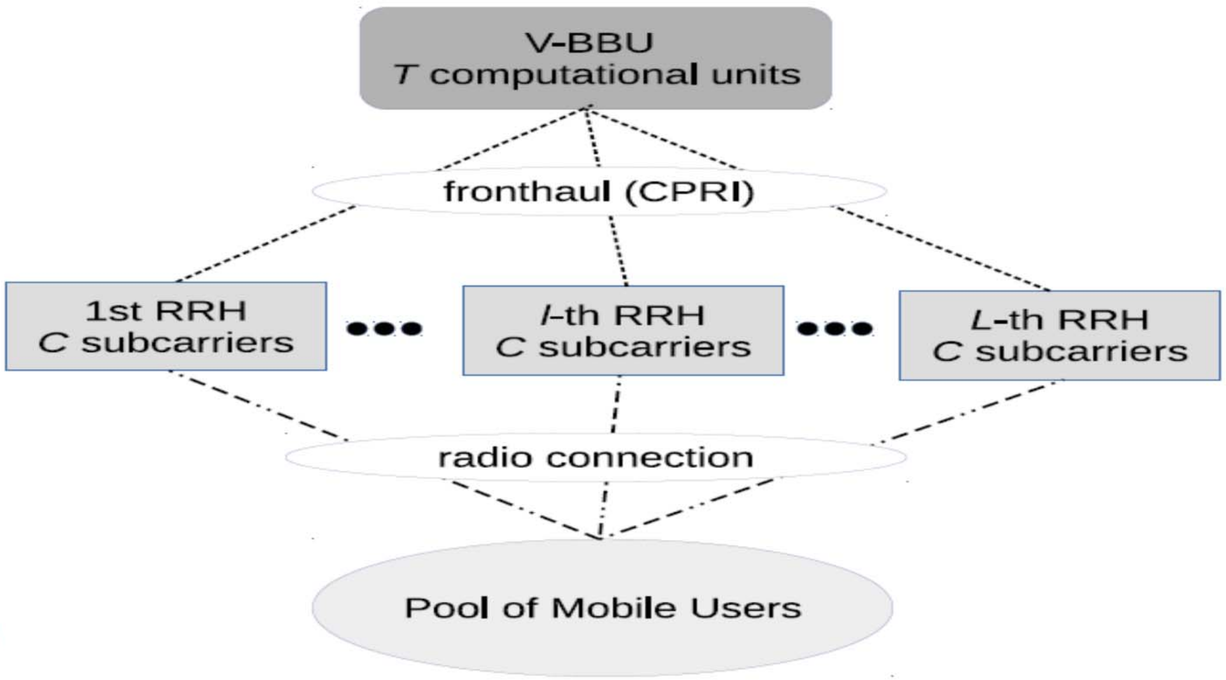
The total number of Remote Radio Heads (RRHs) is *L* and each RRH has *C* subcarriers, which essentially represent units of the radio resource and can be allocated to the accepted calls.

The V-BBU consists of T units (servers) of the computational resource, which are consumed for baseband processing.



Application in 5G Networks (6)

Arriving calls follow a Poisson process with rate . An arriving call requires a subcarrier from the serving RRH and a unit of the computational resource. If these are available (CS policy), then the call is accepted and remains in the system for a generally distributed service time with mean μ^{-1}. Otherwise, the call is blocked and lost.



Application in 5G Networks (7)

The model has a PFS

$$P(\boldsymbol{n}) = \frac{\prod_{l=1}^{L} \frac{a^{n_l}}{n_l!}}{\sum_{\boldsymbol{n}\in\Omega} \prod_{l=1}^{L} \frac{a^{n_l}}{n_l!}}$$

$\boldsymbol{n} = (n_1, \ldots, n_l, \ldots, n_L)$ The number of in-service calls in all RRHs

α=λ/μ the offered traffic-load

To calculate the total CBP, B_{tot}, we distinguish two types of blocking events: 1) those that are caused due to insufficient subcarriers and are represented by the probability, B_{sub}, and 2) those that are caused due to insufficient units of the computational resource and are represented by the probability, B_{res}:

$$B_{tot} = B_{sub} + B_{res}$$

Application in 5G Networks (8)

$$B_{sub} = G \frac{a^C}{C!} \sum_{\mathbf{n} \in \mathbf{\Omega}_{<T}^{1,C}} \prod_{l=2}^{L} \frac{a^{n_l}}{n_l!}$$

$$G = \left(\sum_{\mathbf{n} \in \mathbf{\Omega}} \prod_{l=1}^{L} \frac{a^{n_l}}{n_l!} \right)^{-1}$$

$$\mathbf{\Omega}_{<T}^{1,C} = \left\{ \mathbf{\Omega}^{1,C} \cap \mathbf{\Omega}_{<T} \right\}, \mathbf{\Omega}^{1,C} = \left\{ \mathbf{n} : n_1 = C \right\}, \mathbf{\Omega}_{<T} = \left\{ \mathbf{n} : n_1 + \ldots + n_L < T \right\}$$

$$B_{res} = \sum_{\mathbf{n} \in \mathbf{\Omega}_{=T}} P(\mathbf{n})$$

$$\mathbf{\Omega}_{=T} = \left\{ \mathbf{n} : n_1 + \ldots + n_L = T \right\}$$

Application in 5G Networks (9)

For an efficient calculation of B_{tot}, we can exploit the PFS and propose the following 3-step convolution algorithm:

Step 1) Determine the occupancy distribution of each of the L RRHs, $q_l(j)$, where j=1,…,C and l=1,…,L:

$$q_l(j) = q_l(0)\frac{a^j}{j!}$$

Step 2) Determine the aggregated occupancy distribution $Q_{(-l)}$ based on the successive convolution of all RRHs apart from the lth RRH:

$$Q_{(-l)} = q_1 * q_2 * \ldots * q_{l-1} * q_{l+1} * \ldots * q_L$$

I. D. Moscholios, V. G. Vassilakis, M. D. Logothetis and A. C. Boucouvalas, “State-dependent Bandwidth Sharing Policies for Wireless Multirate Loss Networks”, *IEEE Transactions on Wireless Communications*, vol. 16, issue 8, pp. 5481-5497, August 2017.

Application in 5G Networks (10)

Step 3) Calculate the total CBP, B_{tot}, based on the normalized values of the convolution operation of step 2, as follows:

$$B_{tot} = B_{sub} + B_{res} = q_1(C)Q_{(-1)}(0) + q(T)$$

$$q(T) = G^{-1}\sum_{x=0}^{T} Q_{(-1)}(x)q_1(T-x)$$

Based on the above, the model can be extended to include:

a) multiple service-classes where calls have different subcarrier and computational resource requirements per service-class,
b) different call arrival processes per RRH or group of RRHs, thus allowing for a mixture of arrival processes (e.g., random and quasi-random traffic) and
c) different sharing policies (e.g. CS, BR, MFCR, PrTH) for the allocation of subcarriers in the RRHs or in the V-BBUs.

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Evaluation (1)

A cell of capacity C = 150 channels. K = 2 classes

TABLE I: Traffic characteristics

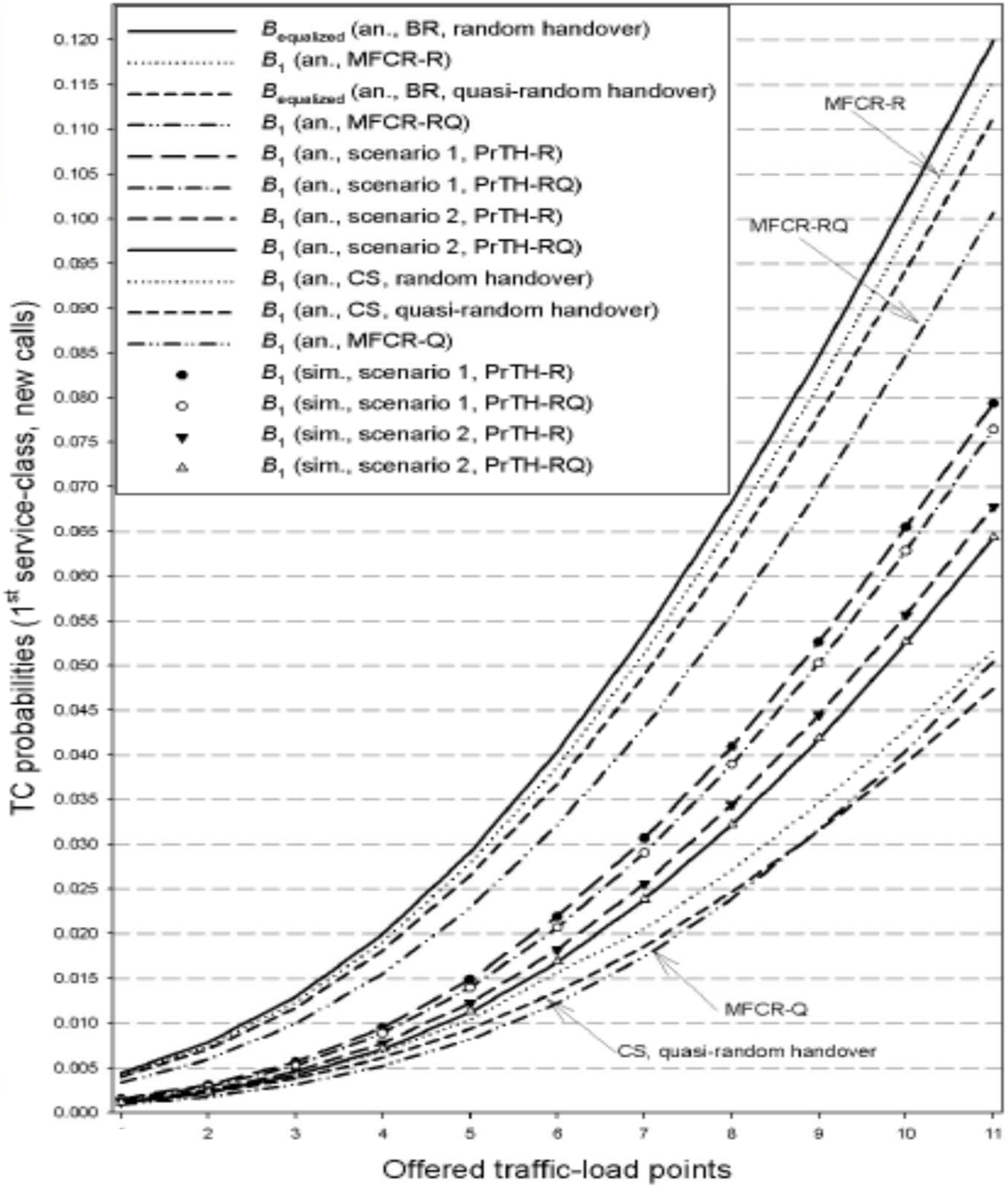
Service-class	Traffic-load (erl)	Bandwidth (channels)	Threshold	Sources	Traffic-load per idle source (erl)
1st (new)	$\alpha_1 = 20.0$	$b_1 = 2$	$n_1^* = 35$	100	$\alpha_{1,fin} = 0.20$
2nd (new)	$\alpha_2 = 5.0$	$b_2 = 7$	$n_2^* = 10$	100	$\alpha_{2,fin} = 0.05$
1st (handover)	$\alpha_3 = 6.0$	$b_3 = 2$	$n_3^* = 70$	100	$\alpha_{3,fin} = 0.06$
2nd (handover)	$\alpha_4 = 1.0$	$b_4 = 7$	$n_4^* = 20$	100	$\alpha_{4,fin} = 0.01$

We consider two scenarios:
(1) New calls of the 1st service-class behave as in the ordinary TH policy, i.e., $p_1(35) = p_1(36) = : : : = p_1(75) = 0$, while new calls of the 2nd service-class are accepted with probability $p_2(10) = p_2(11) = : : : = p_2(20) = 0.5$, and $p_2(21) = 0$,
(2) New calls of the 1st service-class are accepted in the system with probability $p_1(35) = p_1(36) = : : : = p_1(74) = 0.7$ and $p_1(75) = 0$ while new calls of the 2nd service-class are accepted as in scenario 1.
For both scenarios, we assume that $p_3(.) = p_4(.) = 0.95$, for all possible states equal or above the corresponding thresholds.

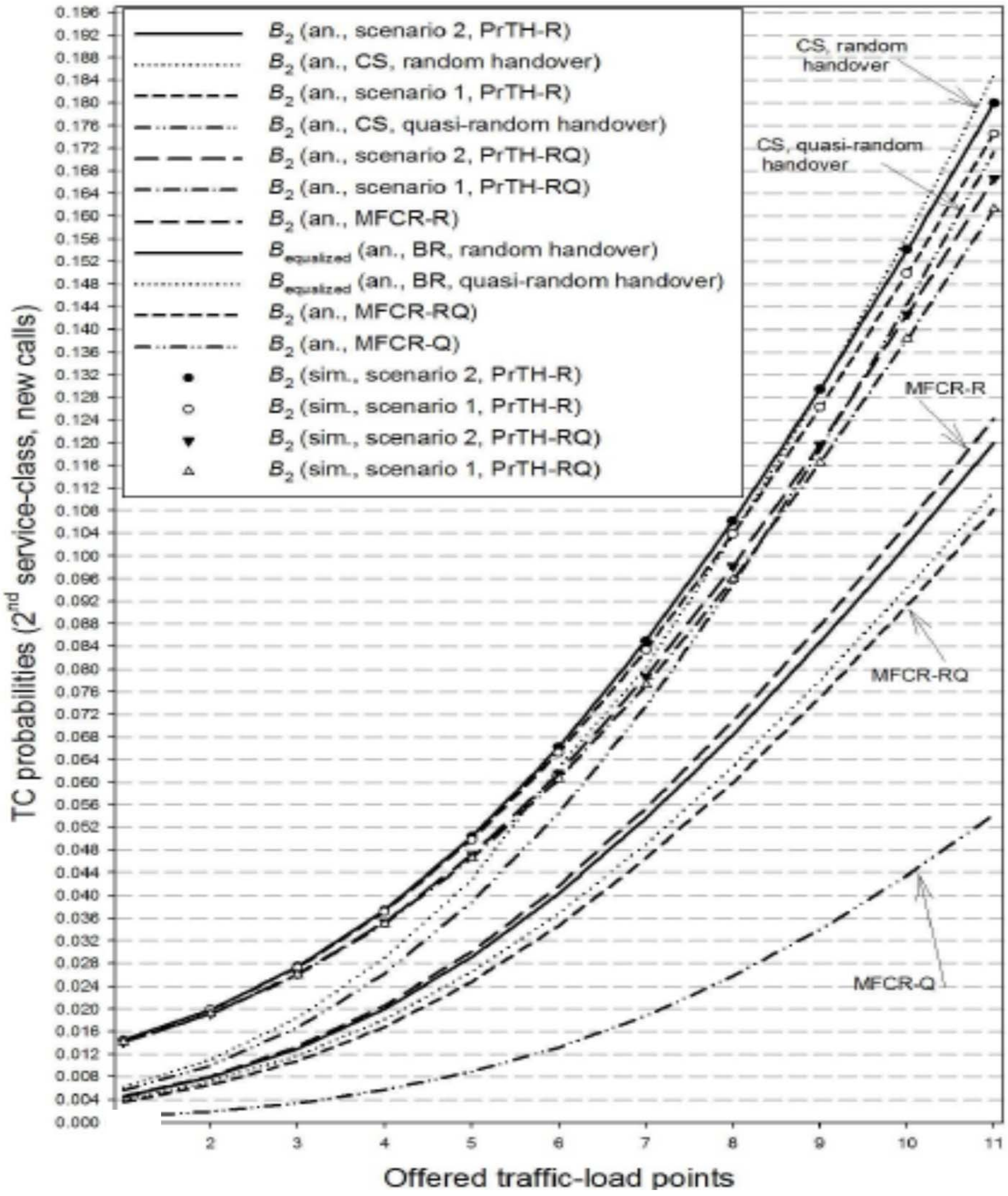
Evaluation (2)

In the MFCR policy, the MFCR parameters are $t_{r,1}= t_{r,3}= 4.7$ channels and $t_{r,2}= t_{r,4}= 0$. In the BR policy, the BR parameters are $t_1 =t_3 =5$ channels and $t_2 =t_4 =0$.

In the x-axis of the Figs the offered traffic load of new and handover calls of both service-classes increases in steps of 1.0, 0.2, 0.5 and 0.1 erl, respectively. So, point 1 refers to: $(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = (20.0, 5.0, 6.0, 1.0)$ while point 11 to: $(\alpha_1, \alpha_2, \alpha_3, \alpha_4) =(30.0, 7.0, 11.0, 2.0)$.



TC probabilities (1st service-class, new calls)
Offered traffic-load points
$B_{equalized}$ (an., BR, random handover)
B_1 (an., MFCR-R)
$B_{equalized}$ (an., BR, quasi-random handover)
B_1 (an., MFCR-RQ)
B_1 (an., scenario 1, PrTH-R)
B_1 (an., scenario 1, PrTH-RQ)
B_1 (an., scenario 2, PrTH-R)
B_1 (an., scenario 2, PrTH-RQ)
B_1 (an., CS, random handover)
B_1 (an., CS, quasi-random handover)
B_1 (an., MFCR-Q)
B_1 (sim., scenario 1, PrTH-R)
B_1 (sim., scenario 1, PrTH-RQ)
B_1 (sim., scenario 2, PrTH-R)
B_1 (sim., scenario 2, PrTH-RQ)
MFCR-R
MFCR-RQ
MFCR-Q
CS, quasi-random handover



B_2 (an., scenario 2, PrTH-R)
B_2 (an., CS, random handover)
B_2 (an., scenario 1, PrTH-R)
B_2 (an., CS, quasi-random handover)
B_2 (an., scenario 2, PrTH-RQ)
B_2 (an., scenario 1, PrTH-RQ)
B_2 (an., MFCR-R)
$B_{equalized}$ (an., BR, random handover)
$B_{equalized}$ (an., BR, quasi-random handover)
B_2 (an., MFCR-RQ)
B_2 (an., MFCR-Q)
B_2 (sim., scenario 2, PrTH-R)
B_2 (sim., scenario 1, PrTH-R)
B_2 (sim., scenario 2, PrTH-RQ)
B_2 (sim., scenario 1, PrTH-RQ)
CS, random handover
CS, quasi-random handover
MFCR-R
MFCR-RQ
MFCR-Q
TC probabilities (2^{nd} service-class, new calls)
Offered traffic-load points

Conclusion

- We presented various bandwidth sharing policies (CS, BR, MFCR, PrTH) for multirate Poisson or quasi-random traffic.
- We showed that CBP can be recursively obtained or via convolution algorithms.
- We showed that the application of these policies is possible in 4G and 5G networks.