Bandwidth Sharing Policies for 4G/5G Networks

Ioannis D. Moscholios
Dept. of Informatics & Telecommunications, University of Peloponnese, Tripolis, Greece
E-mail: idm@uop.gr

The 6th International Conference on Communications, Computation, Networks and Technologies (INNOV), Athens, Greece, Oct. 8-12, 2017
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
A Loss Service System

Calls’ arrival process

Blocked calls lost

Calls in service

Bandwidth Requirement upon arrival

Background (1)
Background (2)

Calls’ Arrival Process

- Random calls – traffic \((\text{infinite number of sources})\)
- Quasi-random calls – traffic \((\text{finite number of sources})\).

Bandwidth Requirement upon arrival

Blocked calls lost

Calls in service

Calls’ arrival process
Bandwidth Requirement upon arrival

Background (3)
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

- Calls’ arrival process
- Calls in service
- Bandwidth Requirement upon arrival
- Blocked calls lost

ON stream traffic
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- Conclusion
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)

Cell of Capacity $C = 8$
1st Service-class: $b_1 = 1$
2nd Service-class: $b_2 = 2$

Traffic Loss

While in service: constant bit rate

Fixed bandwidth requirement upon arrival

1st Service-class calls

Offered traffic

2nd Service-class calls

Exponentially Distributed Interarrival Time
The Complete Sharing (CS) Policy (2)
(in a multirate loss system)

Admission control cases:
Let $j$ be the occupied system’s bandwidth ($j = 0, 1, \ldots, C$) when a call of service-class $k$ arrives in the cell. The call has a bandwidth requirement of $b_k$ b.u. Then:

$$\begin{align*}
\text{if } C - j \geq b_k & \rightarrow \text{the new call is accepted} \\
\text{if } C - j < b_k & \rightarrow \text{the new call is blocked and lost}
\end{align*}$$
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.
The Bandwidth Reservation (BR) Policy (1)

- **QoS guarantee**
- **Fixed bandwidth requirement upon arrival**
- **Traffic Loss**
- **Exponentially Distributed Interarrival Time**

**Cell of Capacity C = 8**
- 1st Service-class: \( b_1 = 1 \)
- 2nd Service-class: \( b_2 = 2 \)

- **While in service:**
  - Constant bit rate
  - Fixed bandwidth requirement upon arrival

- **Offered traffic**
- **Carried traffic**
- **Free Bandwidth Unit**
- **Reserved Bandwidth Unit** (to benefit the 2nd service-class)
Admission control cases:
Let $j$ be the occupied system’s bandwidth ($j = 0, 1, \ldots, C$) 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:

\[
\begin{align*}
& \text{if } C - j - t_k \geq b_k \rightarrow \text{the new call is accepted} \\
& \text{if } C - j - t_k < b_k \rightarrow \text{the new call is blocked and lost}
\end{align*}
\]
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)

QoS guarantee

Cell of Capacity $C = 8$
- $1^{st}$ Service-class: $b_1=1$
- $2^{nd}$ Service-class: $b_2=2$

While in service: constant bit rate

While in service:
- ON

Offered traffic

Carried traffic

Exponentially Distributed Interarrival Time

Traffic Loss

Free Bandwidth Unit

Reserved Bandwidth (to benefit the $2^{nd}$ service-class)

Fixed bandwidth requirement upon arrival

1st Service-class calls

2nd Service-class calls

19 October 2017
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

$$P = 0.4$$

while $\lfloor 0.4 \rfloor = 0$ channels are reserved with probability $1 - (0.4 - \lfloor 0.4 \rfloor) = 0.6$
Admission control cases:
Let $j$ be the occupied system’s bandwidth ($j = 0, 1, \ldots, C$) 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 $C - j - \lfloor t_{r,k} \rfloor > b_k$ → the new call is accepted
- if $C - j - \lfloor t_{r,k} \rfloor = b_k$ → the new call is accepted with prob. $1 - \left( t_{r,k} - \lfloor t_{r,k} \rfloor \right)$
- if $C - j - \lfloor t_{r,k} \rfloor < b_k$ → the new call is blocked and lost
The Probabilistic Threshold Policy (PrTH) Policy (1)

QoS guarantee

Cell of Capacity $C = 8$
1$^{st}$ Service-class: $b_1=1, n_{1,max} = 3$
2$^{nd}$ Service-class: $b_2=2$

Traffic Loss

While in service: constant bit rate

Exponentially Distributed Interarrival Time

Offered traffic

1$^{st}$ Service-class calls

fixed bandwidth requirement upon arrival

2$^{nd}$ Service-class calls

fixed bandwidth requirement upon arrival

Free Bandwidth Unit

Carried traffic

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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.
The Probabilistic Threshold Policy (PrTH) Policy (3)

**Admission control cases:**
Let $j$ be the occupied system’s bandwidth ($j = 0, 1, \ldots, C$) 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:

a) if $C - j \geq b_k$

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

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

b) if $C - j < b_k$ → the call is blocked and lost
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**Basic Definitions (1)**

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

\( j \): occupied system’s bandwidth \((j=0,\ldots,C)\)

\( q(j) \): unnormalized values of the system’s occupancy distribution

\( K \): service-classes accommodated in the cell

\( \lambda_k \): arrival rate of service-class \( k \) \((k=1,\ldots,K)\) calls

\( \mu^{-1}_k \): 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 \( k \)

\( n_{k,\text{max}} \): max. number of in-service calls of service-class \( k \)
Basic Definitions (2)

\( N_k \): number of traffic sources of service-class \( k \)
\( \nu_k \): arrival rate per idle source of service-class \( k \) \( (k=1,…,K) \)
\( \alpha_{k,\text{fin}} = \nu_k / \mu_k \): offered traffic-load per idle source (in erlang)
In the CS Policy (assuming Poisson/random arrivals)

The Erlang Multirate Loss Model (EMLM)

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

Kaufman-Roberts recursion (1981)

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

Determination of Call Blocking Probabilities (CBP) (4)

In the CS Policy (assuming quasi-random arrivals)

The Engset Multirate Loss Model (EnMLM) (1)

\[ q_{\text{fin}}(j) = \begin{cases} 
1, & \text{for } j = 0 \\
\frac{1}{N} \sum_{k=1}^{K} (N - y_k(j - b_k)) a_{k,\text{fin}}(j - b_k) b_k q_{\text{fin}}(j - b_k), & \text{for } j = 1, \ldots, C \\
0, & \text{otherwise} 
\end{cases} \]

\[ y_k(j) = \begin{cases} 
a_k q(j - b_k), & \text{for } j \leq C \\
q(j), & \text{otherwise} 
\end{cases} \]


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)

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

For \( K = 1 \) \( \rightarrow \)

\[
P_{b_1} = \frac{\binom{N}{C} (\alpha_1)^C}{\sum_{i=0}^{C} \binom{N}{i} (\alpha_1)^i}
\]

Engset formula (1918)

For \( N_k \rightarrow \infty \), \( q(j) \) results in Kaufman/Roberts recursion (EMLM)
In the BR Policy (assuming Poisson/random arrivals)

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

Roberts recursion (1983)

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

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

CBP

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

\[ J. \text{ Roberts, “Teletraffic models for the Telecom 1 Integrated Services Network”, Proc. 10th ITC, paper 1.1-2, Montreal 1983.} \]
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)

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

\[
ya_k(j-b_k) = \begin{cases} 
a_{k,\text{fin}}, & \text{for } j \leq C - t_k \\
0, & \text{otherwise}
\end{cases}
\]

\[
y_k(j) = \begin{cases} 
\frac{a_k q(j-b_k)}{q(j)}, & \text{for } j \leq C - t_k \\
0, & \text{otherwise}
\end{cases}
\]

Determined via the EMLM/BR
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)

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

Determination of Call Blocking Probabilities (CBP) (9)

In the MFCR Policy (assuming Poisson/random arrivals)

The MFCR- Random model (MFCR-R)

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

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

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

Determination of Call Blocking Probabilities (CBP) (10)

In the MFCR Policy (assuming quasi-random arrivals)

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

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

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

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)

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

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

\[
q_k(j) = \begin{cases} 
q_k(0) \frac{a_k^i}{i!}, & \text{for } 1 \leq i \leq n_{k,\text{max}} \text{ and } j = ib_k \\
\prod_{i=1}^{i-1} p_k(x)a_k^i, & \text{for } n_{k,\text{max}} < i \leq \left\lfloor \frac{C}{b_k} \right\rfloor \text{ and } j = ib_k \\
q_k(0) \frac{1}{i!}, & \text{otherwise} \\
0, & \text{otherwise}
\end{cases}
\]
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)

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

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

$$q_k * q_r = \left\{ q_k(0)q_r(0), \sum_{x=0}^{1} q_k(x)q_r(1-x), ..., \sum_{x=0}^{C} q_k(x)q_r(C-x) \right\}$$
In the PrTH Policy (assuming Poisson/random arrivals)

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

**Step 3:** CBP of service-class \( k \)

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

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

\[
q(0) = Q_{(-k)}(0)q_k(0) / G
\]

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

$$q_k(j) = q_k(0) \binom{N_k}{i} a_{k,fin}^i, \text{ for } 1 \leq i \leq n_k^* \text{ and } j = ib_k$$

$$q_k(0) \binom{N_k}{i} \prod_{x=n_k^*}^{i-1} p_k(x) a_{k,fin}^i, \text{ for } n_k^* < i \leq \left\lfloor C / b_k \right\rfloor \text{ and } j = ib_k$$

$$0, \text{ otherwise}$$
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 \( k \)

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

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

\[
q(0) = Q_{(-k)}(0)q_k(0) / G
\]

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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 $\gamma_k, k=1,\ldots,K$ the average channel gain of the $k$th interval.

Considering $L$ subcarrier requirements and $K$ average channel gains, there are $LK$ service-classes.
Definitions – Assumptions (2)

A newly arriving service-class \((k,l)\) call \((k=1,\ldots,K\) and \(l=1,\ldots,L)\) 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 \(\gamma_k\).

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 \(\mu^{-1}\).

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 \(\gamma_k\) we use the Shannon theorem:

\[
R = \frac{B}{M} \log_2 (1 + \gamma_k p_k)
\]
Application in 4G Networks (3)

Definitions – Assumptions (3)

Assuming that calls follow a Poisson process with rate $\lambda_{kl}$ 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 $\pi(n)$

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

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

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

$$p_{kl} = \lambda_{kl} / \mu$$

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

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
A recursive formula for the calculation of $q(j_1, j_2)$ in the case of the CS policy

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

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

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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.
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.
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.

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.
Arriving calls follow a Poisson process with rate $\lambda$. 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 $\mu^{-1}$. Otherwise, the call is blocked and lost.
The model has a PFS

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

\[ n = (n_1, \ldots, n_l, \ldots, n_L) \]

The number of in-service calls in all RRHs

\[ \alpha = \lambda / \mu \] 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)

\[
B_{sub} = G \frac{a^C}{C!} \sum_{n \in \Omega_{<T}} \prod_{l=2}^{L} \frac{a^{n_l}}{n_l !}
\]

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

\[
\Omega_{<T}^{1,C} = \left\{ \Omega_{<T}^{1,C} \cap \Omega_{<T} \right\}, \Omega_{<T}^{1,C} = \{ n : n_1 = C \}, \Omega_{<T} = \{ n : n_1 + \ldots + n_L < T \}
\]

\[
B_{res} = \sum_{n \in \Omega_{=T}} P(n)
\]

\[
\Omega_{=T} = \{ n : n_1 + \ldots + n_L = T \}
\]
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 $l$th RRH:

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

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

We consider two scenarios:

1. New calls of the 1st service-class behave as in the ordinary TH policy, i.e., \( p_1(35) = p_1(36) = \ldots = p_1(75) = 0 \), while new calls of the 2nd service-class are accepted with probability \( p_2(10) = p_2(11) = \ldots = p_2(20) = 0.5 \), and \( p_2(21) = 0 \).

2. New calls of the 1st service-class are accepted in the system with probability \( p_1(35) = p_1(36) = \ldots = p_1(74) = 0.7 \) 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.

### TABLE I: Traffic characteristics

<table>
<thead>
<tr>
<th>Service-class</th>
<th>Traffic-load (erl)</th>
<th>Bandwidth (channels)</th>
<th>Threshold</th>
<th>Sources</th>
<th>Traffic-load per idle source (erl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{st}) (new)</td>
<td>( a_1 = 20.0 )</td>
<td>( b_1 = 2 )</td>
<td>( n_1^* = 35 )</td>
<td>100</td>
<td>( a_{1,fin} = 0.20 )</td>
</tr>
<tr>
<td>2(^{nd}) (new)</td>
<td>( a_2 = 5.0 )</td>
<td>( b_2 = 7 )</td>
<td>( n_2^* = 10 )</td>
<td>100</td>
<td>( a_{2,fin} = 0.05 )</td>
</tr>
<tr>
<td>1(^{st}) (handover)</td>
<td>( a_3 = 6.0 )</td>
<td>( b_3 = 2 )</td>
<td>( n_3^* = 70 )</td>
<td>100</td>
<td>( a_{3,fin} = 0.06 )</td>
</tr>
<tr>
<td>2(^{nd}) (handover)</td>
<td>( a_4 = 1.0 )</td>
<td>( b_4 = 7 )</td>
<td>( n_4^* = 20 )</td>
<td>100</td>
<td>( a_{4,fin} = 0.01 )</td>
</tr>
</tbody>
</table>
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: $(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = (30.0, 7.0, 11.0, 2.0)$. 
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.