# Optimization and Performance Analysis of High Speed Mobile Access Networks

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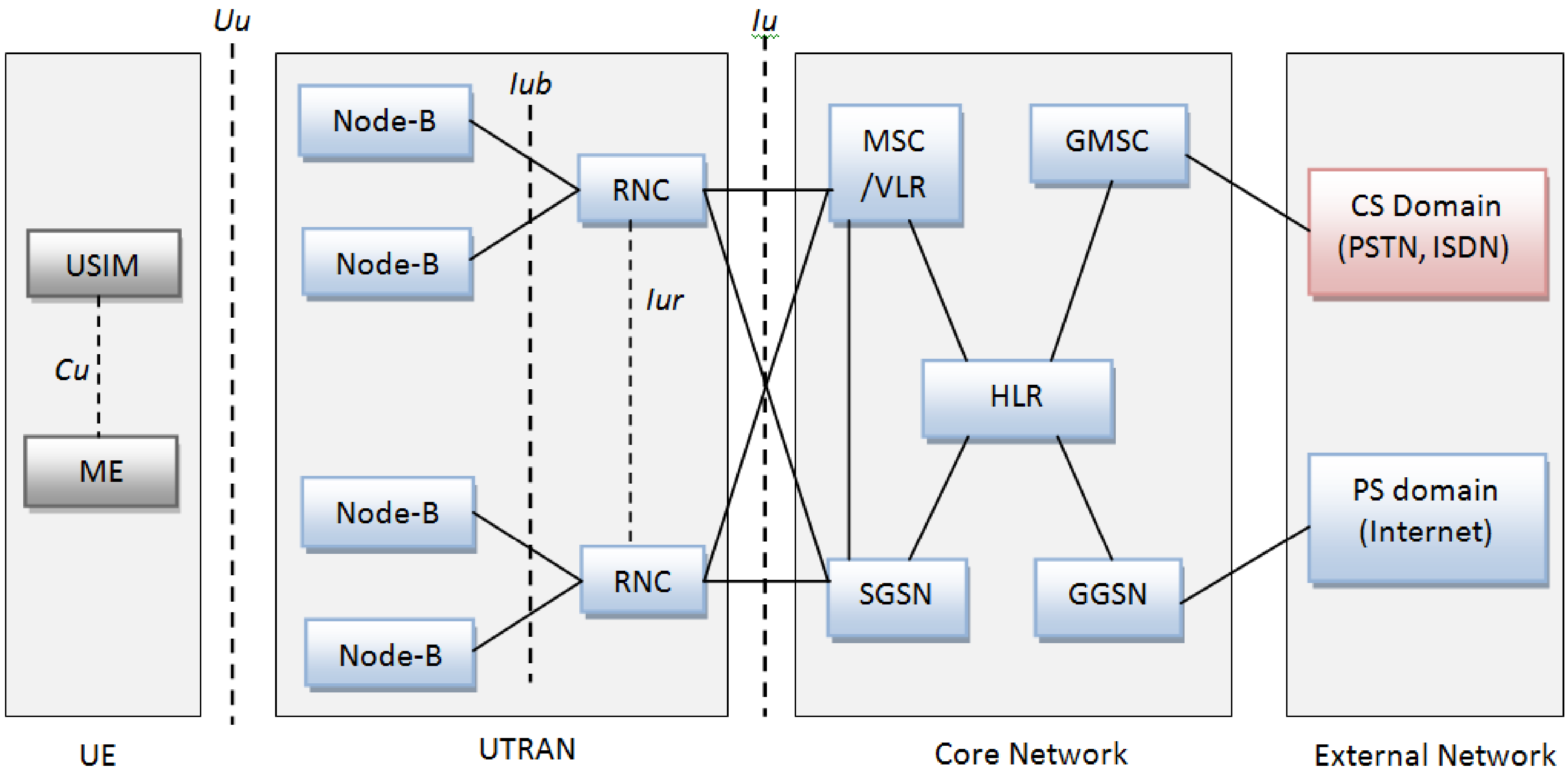
# Overview

- Overview of high speed broadband wireless networks
  - Key technologies and architecture
- Main achievements
  - Overview of the completed tasks during the thesis work
- HSPA transport flow control and congestion control
  - Theoretical approach
  - Analytical modeling
  - Performance analysis and results comparison
- Conclusion and outlook

# High speed broadband wireless networks

- Universal Mobile Telecommunication System (UMTS)
  - Standardised in 3GPP release 99 and radio interface: WCDMA
  - 64 kbit/sec circuit switched, 384 kbit/sec packet switched services
  - Bearer services, Location services and compatible with GSM
- High Speed Packet Access Networks (HSPA)
  - Downlink: HSDPA, standardised in 3GPP release 5
    - Higher data rates for packet services: 1.8, 3.6, 7.2 and 14 Mbit/sec
    - Key features: Hybrid ARQ, fast packet scheduling, adaptive modulation and coding (AMC)
    - IP Multimedia System (IMS)
  - Uplink: HSUPA, standardised in 3GPP release 6
    - Enhanced uplink data rates up to 5.76 Mbit/sec and
    - Key improvements as in the downlink
- Long Term Evolution (LTE)
  - Standardised in 3GPP release 8:
  - all IP-network, New OFDMA, MIMO based radio interface
  - Not backward compatible with previous UMTS

# HSPA architecture (UMTS, HSDPA, HSUPA)




*UE: User Equipment*
*VLR: Visitor Location Register*
*CS: Circuit Switch*
*SGSN: Serving GPRS Support Node*
*USIM: Universal Subscriber Identity Module*
*MCS: Mobile service Switching Centre*
*GGSN: Gateway GPRS support Node*
*PSTN: Public Switched Telephone Network*
*ME: Mobile Equipment*
*HLR: Home Location Register*
*EIR: Equipment Identity Register*
*UTRAN: UMTS Terrestrial Radio Access Network*
*RNC: Radio Network Controller*
*PS: Packet Switch*
*GMSC: Gateway MSC*

# Key achievements

- Design and development of a comprehensive HSPA simulator
  - Implementation of all UTRAN based protocols and end-user protocols
  - Design and implementation of uplink and downlink MAC schedulers
- HSPA transport feature development
  - Adaptive credit-based flow control schemes → *Journal of Communications 2009 (IEEE), Academy Publisher*
  - Effective congestion control schemes → *Journal Publication, IEEE VTC magazine, December 2009*
- Design and development of analytical models
  - A Markov model of congestion control
  - A combined Markov model of flow control and congestion control
- Design and development of a detailed LTE system simulator
  - E-UTRAN and end-user protocols
  - A comprehensive MAC scheduler and IP based transport QOS scheduler

# Key achievements

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  - All UTRAN based protocols and end-user protocols
  - Design of uplink and downlink MAC schedulers
- HSPA transport feature development
  - A adaptive credit-based flow control scheme and
  - Effective congestion control schemes
- Design and development of analytical models
  - A Markov model of congestion control
  - **A combined Markov model of flow control and congestion control**
- Design and development of a detailed LTE system simulator
  - E-UTRAN and end-user protocols
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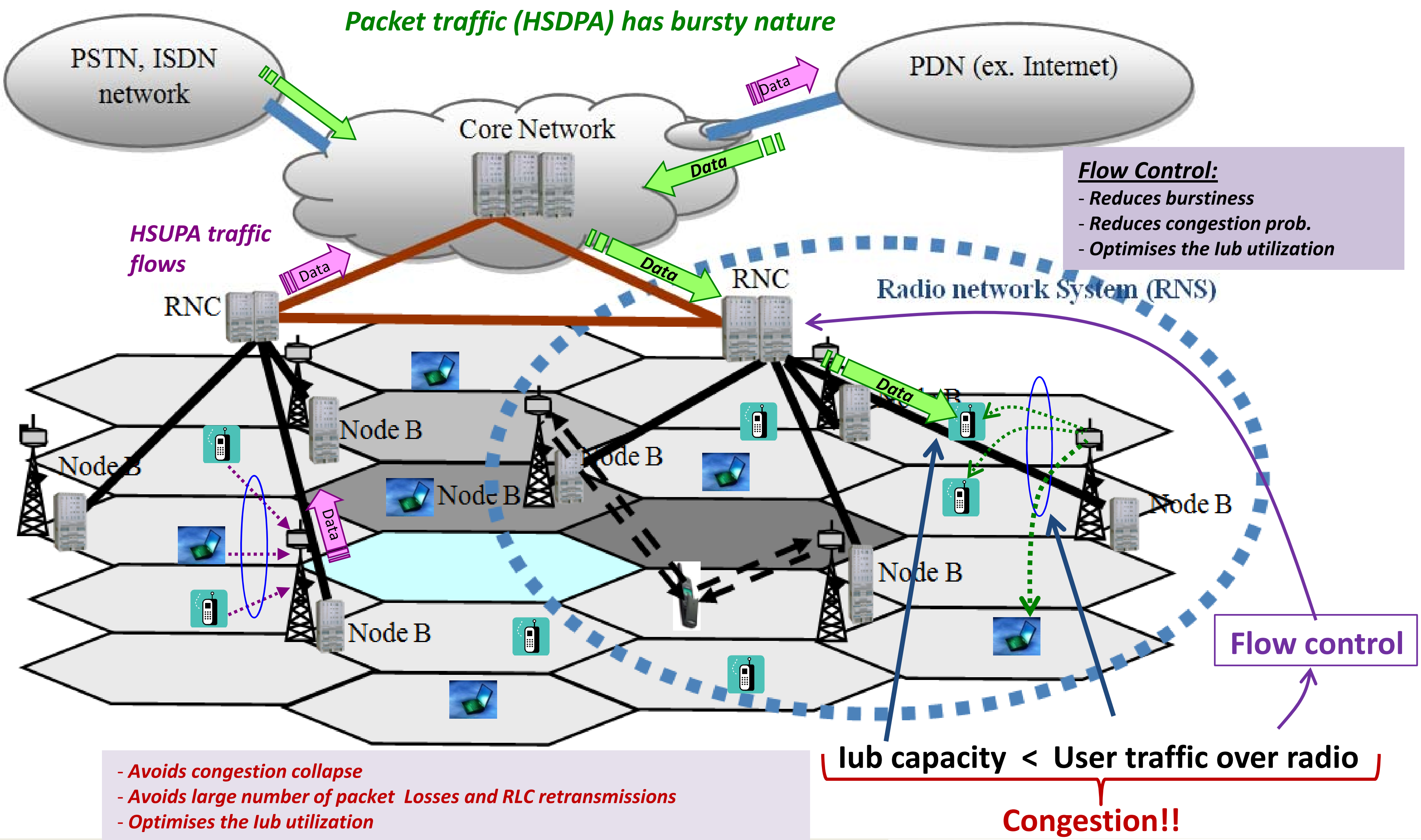
Complete modelling and analysis

# HSDPA FC and CC overview

*Packet traffic (HSDPA) has bursty nature*




***Flow Control:***
- *Reduces burstiness*
- *Reduces congestion prob.*
- *Optimises the Iub utilization*

- *Avoids congestion collapse*
- *Avoids large number of packet Losses and RLC retransmissions*
- *Optimises the Iub utilization*

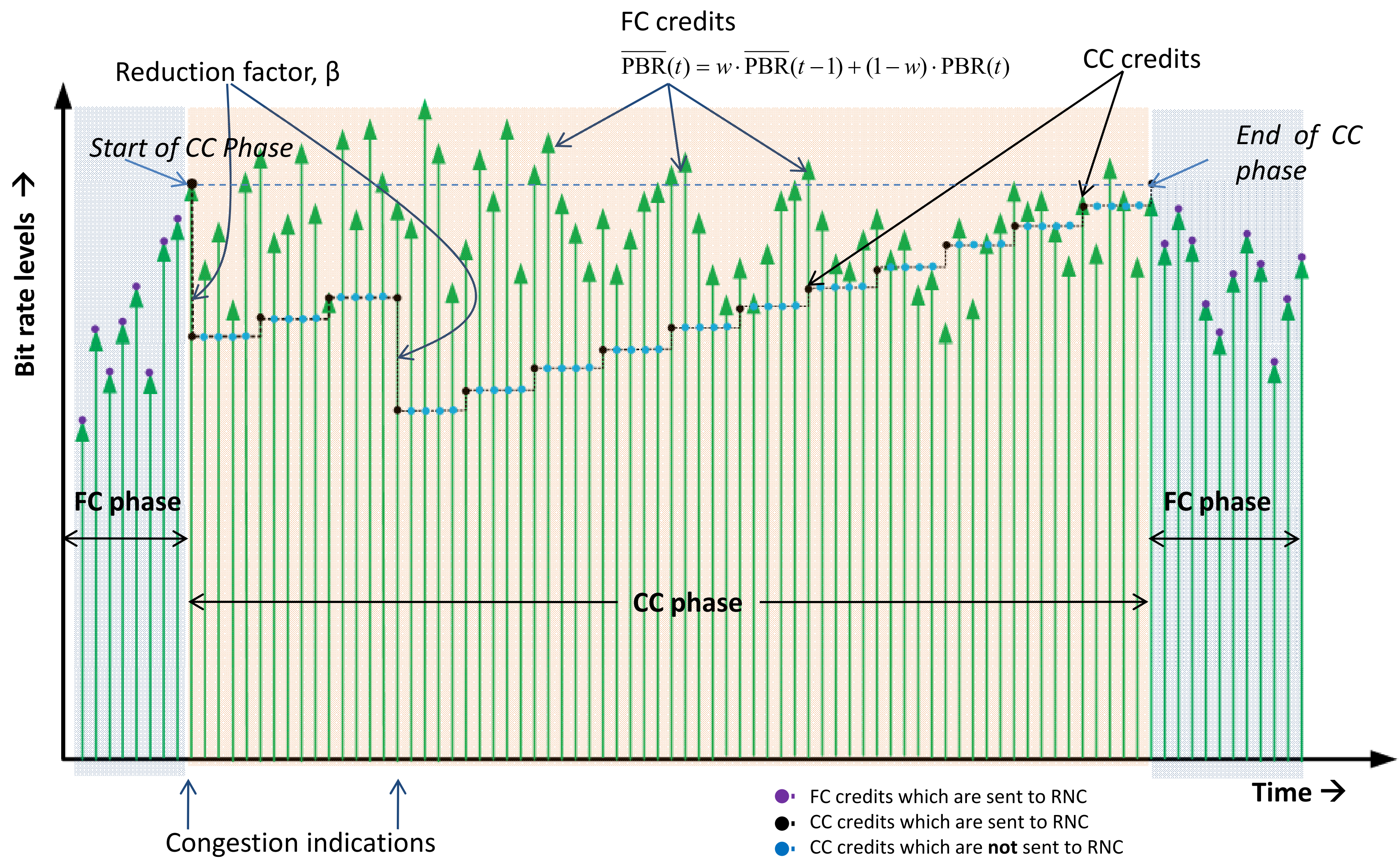
# HSDPA flow control and congestion control

- Adaptive credit-based flow control
  - Flow control adapts the Iub flow to the available throughput at the air interface for individual user flows
  - Credit-based flow control
    - Continuous loop control using the Provided Bit Rate (PBR).

      $$\overline{PBR}(t) = w \cdot \overline{PBR}(t-1) + (1-w) \cdot PBR(t) \quad \text{where } w \text{ is the weight factor}$$

    - Buffer management (to optimise the radio utilisation)
- Congestion control
  - Bursty traffic over the limited transport network causes congestion resulting in many packet losses
  - Wastage of scarce radio resources, network resources and degradation of overall end-to-end performance
  - Requirement: a proper congestion control mechanism to adapt radio capacity to the available transport capacity adaptively
  - Congestion control mechanism includes
    - **Preventive** and **reactive** congestion **detection** schemes and input traffic **control** scheme

# MAC-d flow variation in FC and CC



# Analytical modeling of FC and CC

- Prerequisites
  - Two state variables for FC and CC
  - Time step in CC is several times longer (5) than the time step in FC
  - Maximum level reached under CC depends on starting FC level

- Assumptions
  - The interarrival times of CIs are independent and identically distributed
  - Number of users remains constant (stationary system)
  - Constant transmission delay for CA signals
  - Per-user buffer occupancy at Node-B is not considered for FC modelling

# Joint Markov chain

## State representation

three non-negative integers, $[i, j, k]$

- Bit rate level in FC state, $i$ $[i = 1, 2, 3, \dots m]$
- Bit rate level in CC state, $j$ $[j = 1, 2, 3, \dots m]$
- Time steps in CC state, $k$ $[k = 1, 2, 3, \dots 5]$

## The number of states

The total number of FC states and CC states $\Big\} = m + \dfrac{m \cdot (m+1) \cdot 5}{2}$

## State transition

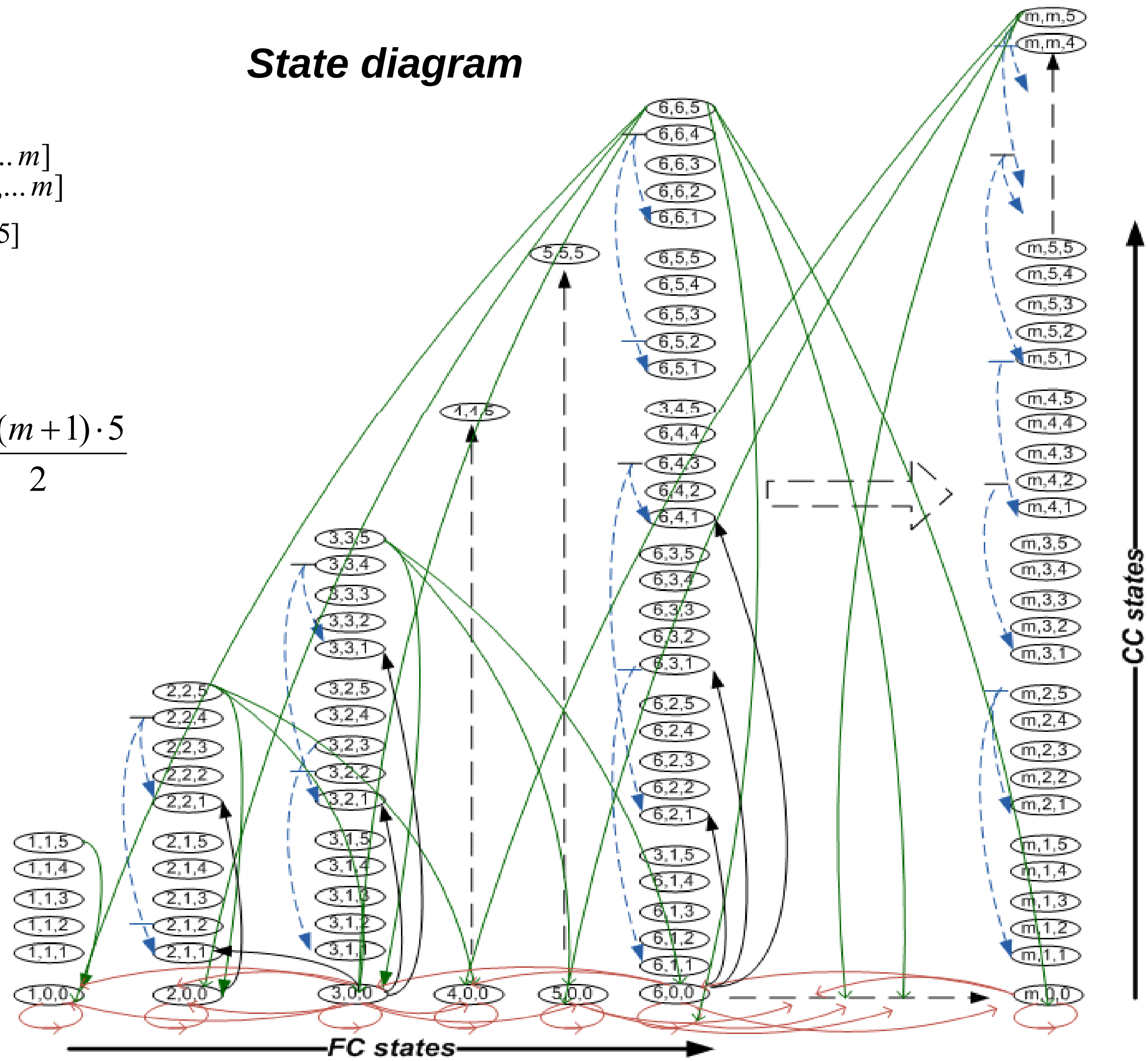
FC to FC transitions →

FC to CC transitions →

CC to CC transitions →

CC to FC transitions →

***State diagram***



# Markov model: input parameters

- Stationary FC state probability matrix, *PBRm*

$$PBRm = \left[pbr_j\right]_{1\times m} \quad \text{where} \quad j = 1\ldots m$$

(The stationary FC state probability matrix is derived from a trace file which is taken from a dedicated radio simulation.)

- The congestion indication arrival probability matrix, $A_{ci}$

$$A_{ci} = [q_i]_{1\times(1+d_{\max})}$$

$$\text{where} \quad q_i = \Pr[\text{exactly } i \text{ CI signals during } \Delta T]; \quad \mathrm{i} = 0\cdots \mathrm{d}_{\max}$$

(This parameters, the CI arrival probability within a step is taken from a trace which is taken from **a fast queuing simulator** which is designed and developed by the author)

# Transition probability calculations

- Flow control transition probability matrix

$$P_{fctofc} = [p_{ij}]_{m \times m}$$

$$p_{ij} = \Pr[FC(T + \Delta T) = j \mid FC(T) = i]$$

- State transition probability from FC state, i to FC state, j

$$p_{(i,0,0)(j,0,0)} = q_0 p_{ij}$$

where $q_0$ is the probability that no CI arrivals occurs within a given FC interval

- State transition probability from FC state to CC state

$$p_{(i,0,0)(i,l,1)} += q_n \qquad \forall\, l = i \times \alpha^n; \quad n = 1 \ldots d_{\max}$$

where $\alpha = 1 - \beta$ and

$d_{\max}$ max number of CI arrivals within a single step

# Transition probability calculations cont.

- From CC state to CC state transition probabilities
  - Up: in case of no arrivals

$$p_{(i,j,k)(i,j,k+1)} = q_0 \quad \text{for} \quad k = 1,2,3,4$$

$$p_{(i,j,k)(i,j+1,1)} = q_0 \quad \text{for} \quad k = 5$$

  - Down: due CI arrivals

$$p_{(i,j,k)(i,l,1)} += q_n \qquad \forall\, l = j \times \alpha^n; \quad n = 1 \ldots d_{\max} \text{ and } k = 1 \ldots 5$$

- From CC state to FC state transition probabilities

$$p_{(i,i,5)(l,0,0)} = q_0 \; p_{il} \qquad l \text{ is the next FC state and } i \text{ is the starting FC state before the MAC-d flow enters the CC state}$$

# State probabilities and average throughput

- Transition probability matrix, with square dimension $n_t$

$$P = \left[p_{ijk}\right]_{n_t \times n_t} \qquad \text{where } i = 1,2,3,\ldots., n_{fc}$$
$$j = 1,2,3,\ldots., n_{cc}$$
$$k = 1,2,3,\ldots., n_{st}$$

- Stationary state probabilities matrix, π

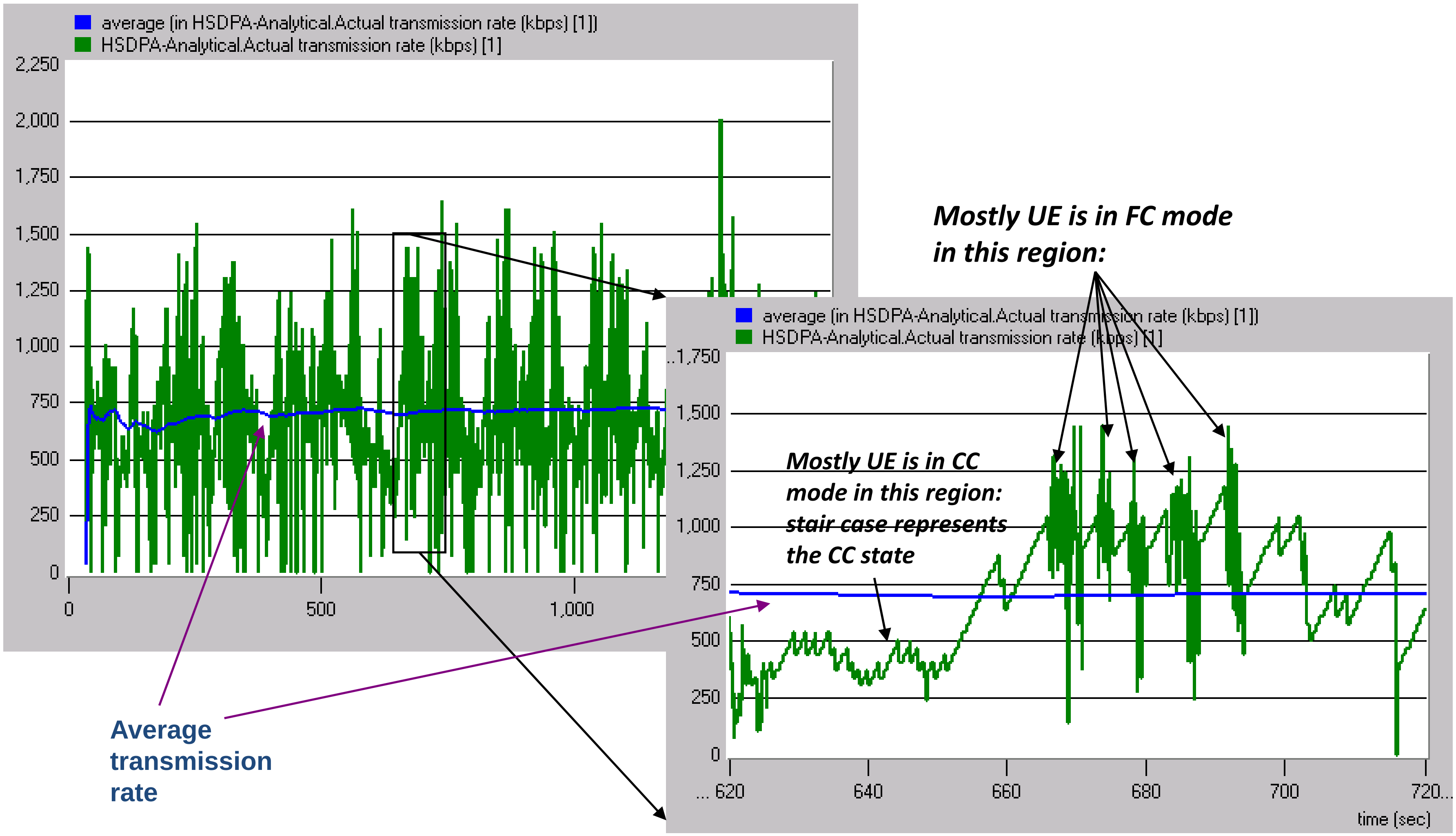
$$\pi = \pi \cdot \mathrm{P} \qquad \text{Where } \pi \text{ denotes the state vector, } [\pi_0, \pi_1, \pi_2, \pi_3 \ldots\ldots, \pi_{n_t}]$$

- Average throughput $= bitRateStepSize \times \sum_{i=1}^{n_t} i\pi_i \quad bit/\sec$
  - Example, size of the bit rate level is 33.6 kbps for the given consideration

# Results analysis: Simulation and analytical

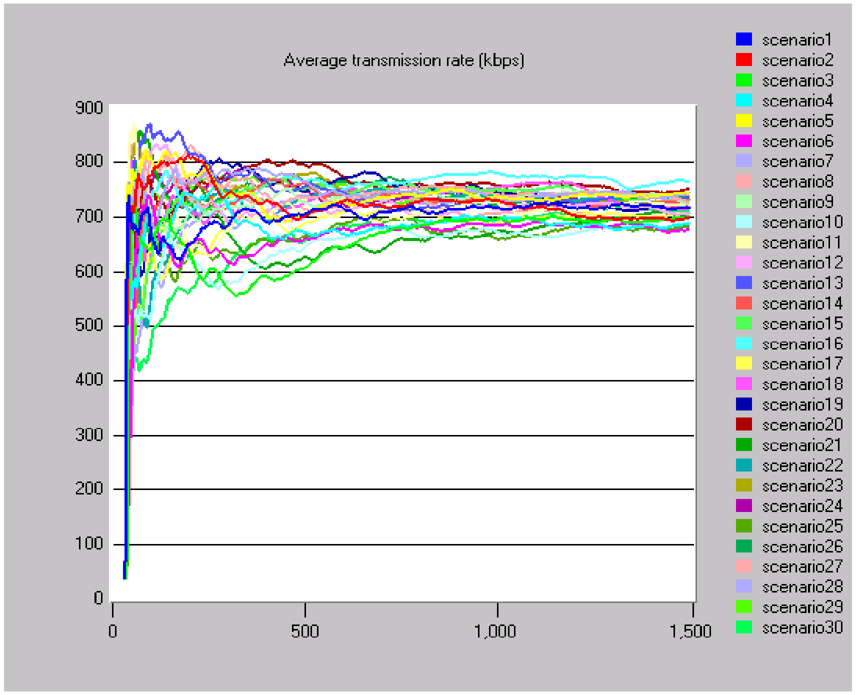
- Parameter configuration
  - Common parameters (simulation and analytical)
    - FC cycle time = 100 ms
    - CC AIMD cycle time = 500 ms
    - FC and CC Step size = 33.6 kbps
    - Reduction factor β = 0.25
    - Safe timer = 80 ms
    - ATM bandwidth = 2Mbps
  - Simulation specific
    - Traffic models: FTP and HTTP traffic models
    - User constellation: 18 users, 1 FTP user who downloads a large file during the simulation time and uses the probability distribution used for the analytical model. All other 17 users generate HTTP traffic.
    - The simulation duration is 2000 sec and 32 replications are used to determine the confidence interval.

# Simulation results: transmission data rate

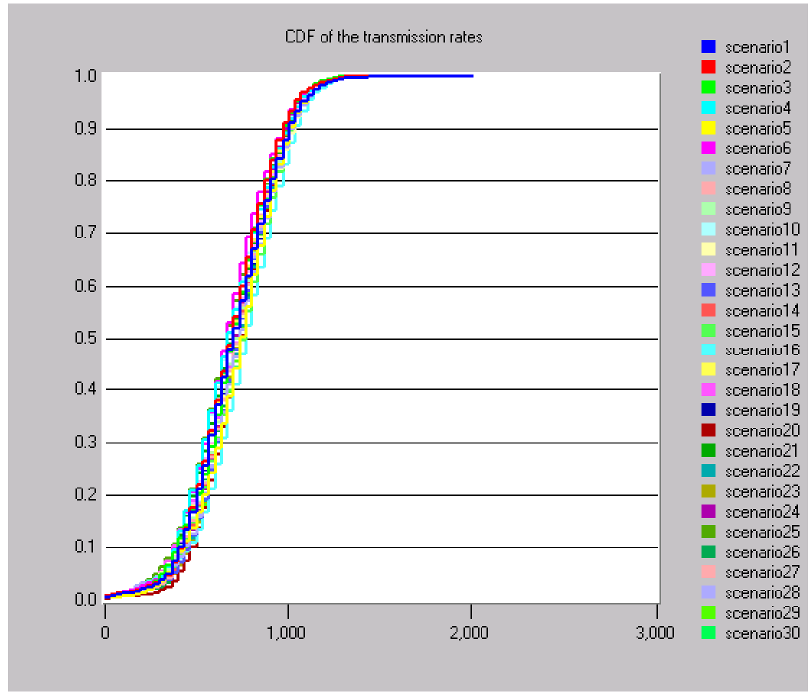


# Simulation results: 30 replications

Average throughputs




CDF of throughputs




**Statistical evaluation**

Mean = 719.60 kbit/sec

Standard deviation = 21.13 kbit/sec

95%confidence interval

= [713.05 kbit/sec– 726.16 kbit/sec]

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Replications, i* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* |
| Mean, $\overline{Y}_i$ | 713 | 697 | 700 | 688 | 743 | 676 | 740 | 726 | 720 | 689 | 723 | 706 | 734 | 726 | 743 |
| *Replications, i* | *16* | *17* | *18* | *19* | *20* | *21* | *22* | *23* | *24* | *25* | *26* | *27* | *28* | *29* | *30* |
| Mean, $\overline{Y}_i$ | 763 | 704 | 715 | 724 | 749 | 702 | 742 | 730 | 717 | 681 | 732 | 718 | 729 | 736 | 710 |

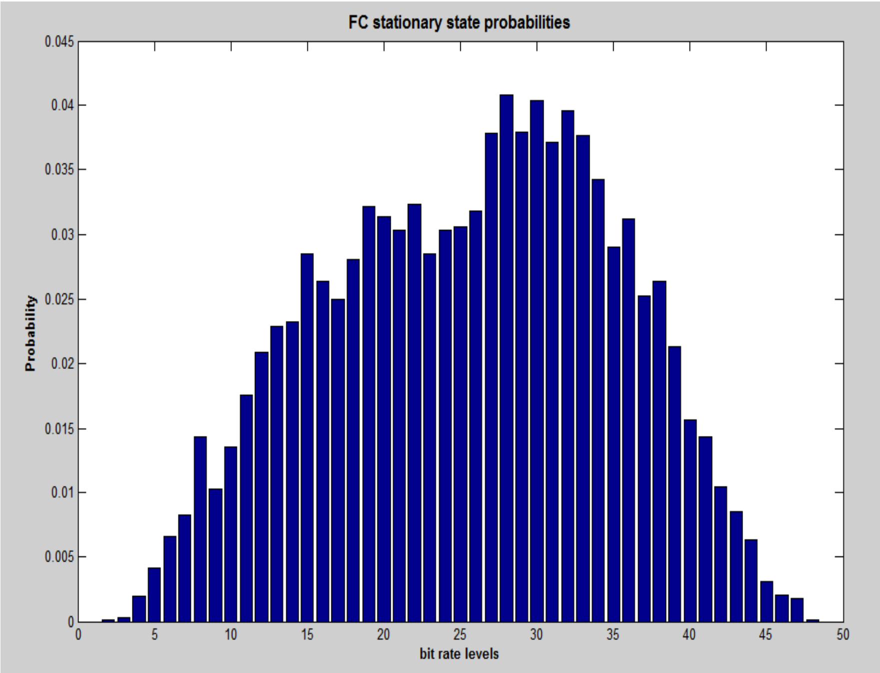
Probability mass function of the bit rate levels (number of MAC-ds)

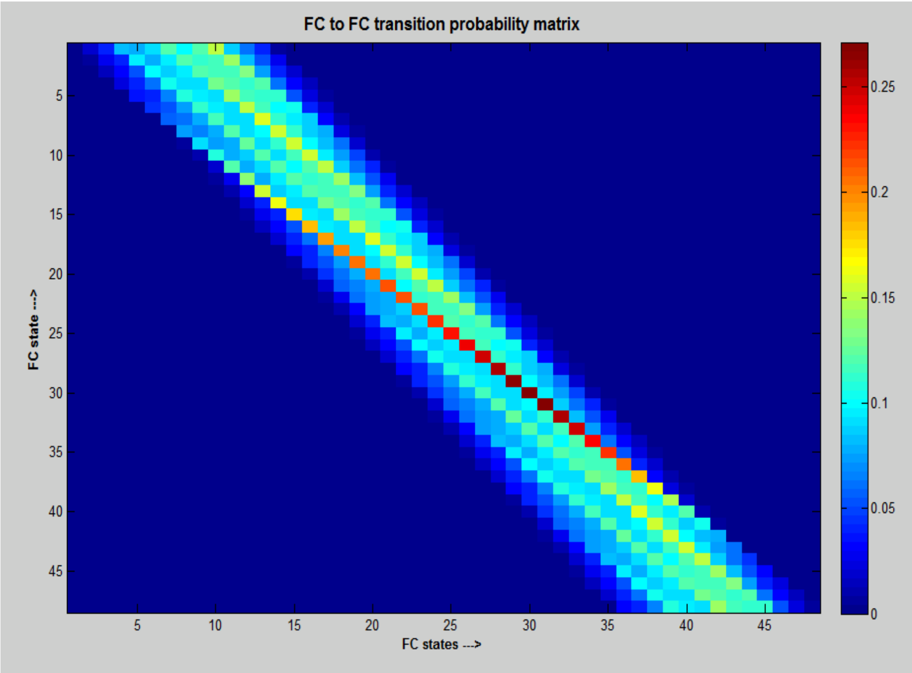
*FC state stationary probabilities*

FC filter formula

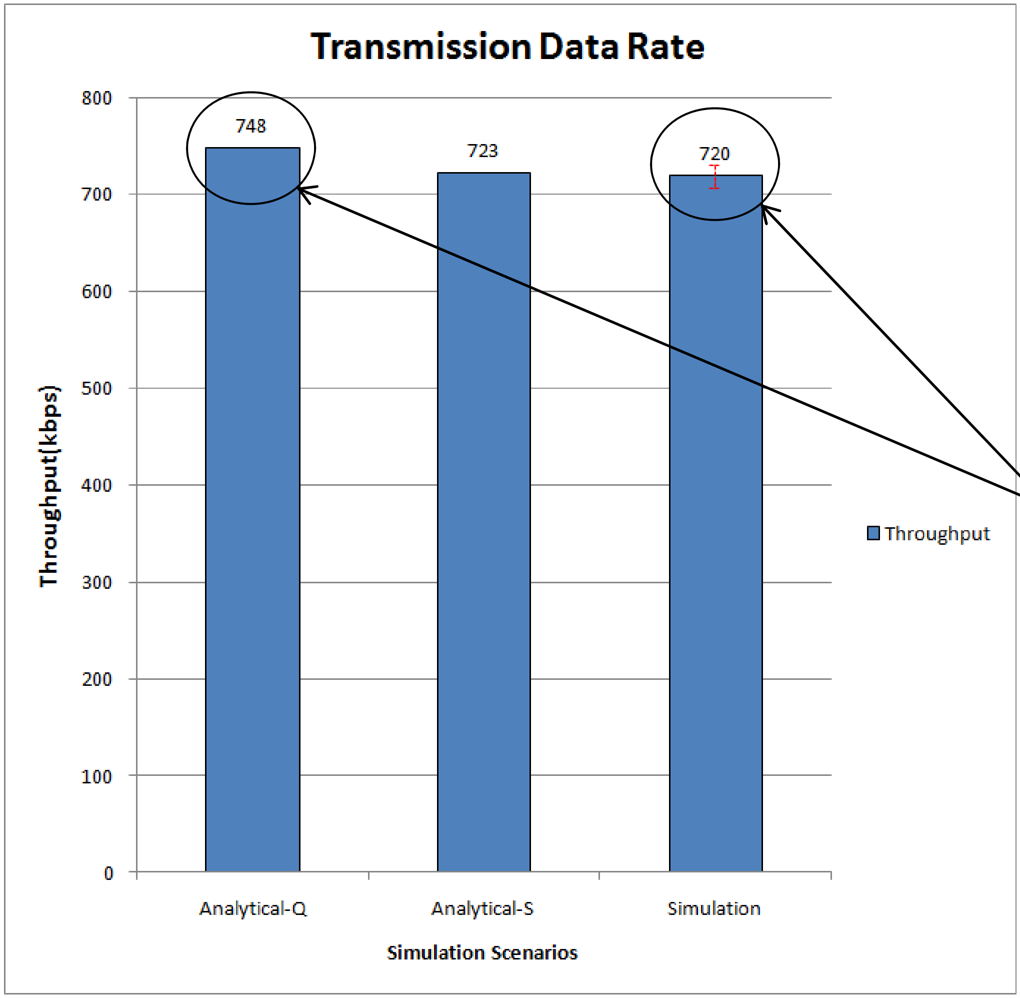
$$\overline{PBR}(t) = w \cdot \overline{PBR}(t-1) + (1-w) \cdot PBR(t)$$

$w$ is the weight factor



# Analytical and simulation results comparison




**Scenarios**

- Analytical model-Q:
  CI trace from the fast queuing simulator
- Analytical model-S
  CI trace from the detailed system simulator
- Simulation

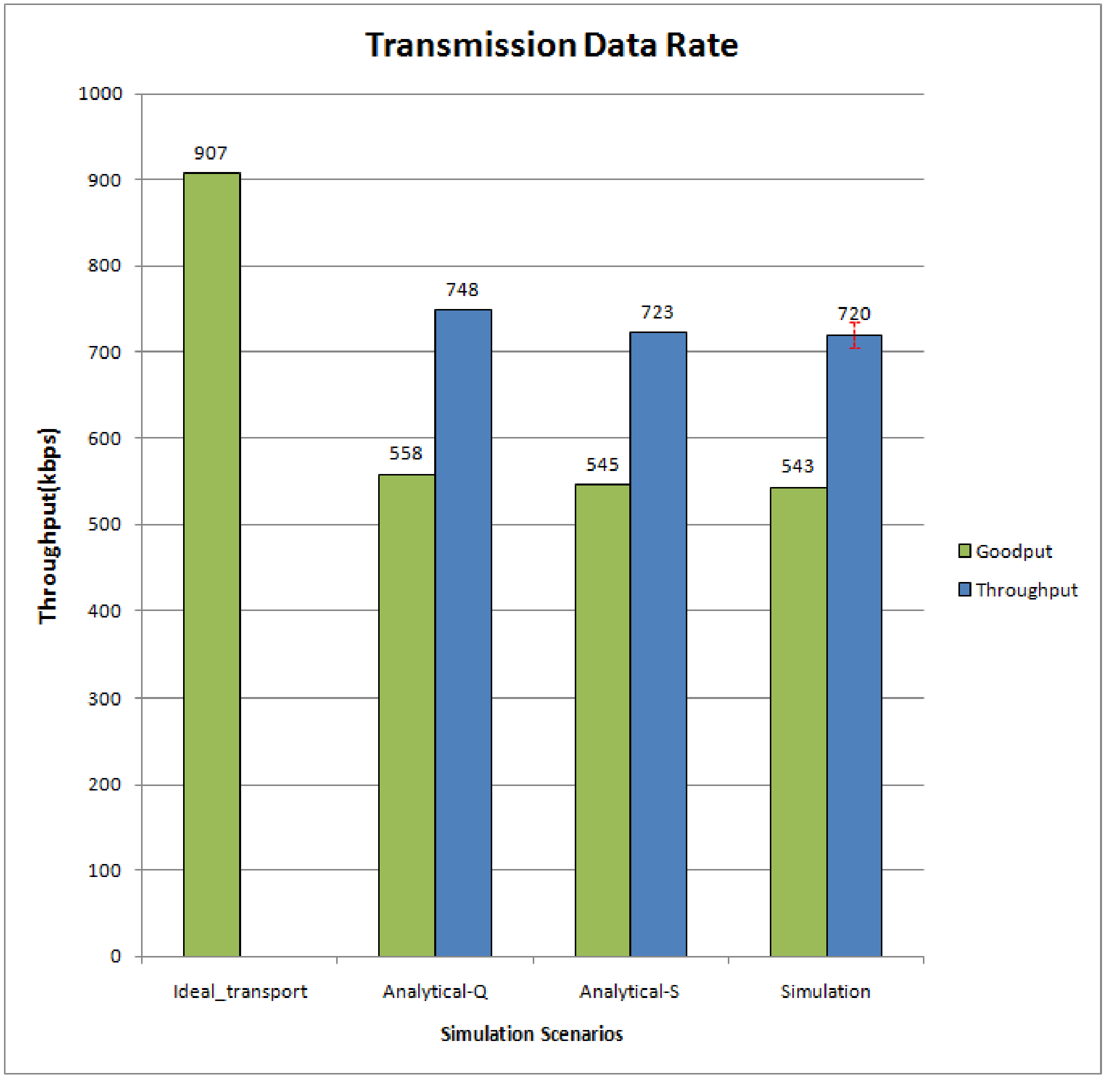
| | Analytical-S | Analytical-Q |
|---|---|---|
| Probability of no CI arrival within a single step, $q_0$ | 95.83% | 94.74% |

Throughput difference (analytical-Q)

- Additional RLC retransmissions (1%,- 0.41%)
- Losses are uniformly distributed
- Effect of TCP the TCP protocol
- All other protocol simplifications and assumption ..

➡ Goodput comparison provide more close agreement

# Results comparison cont.




| | Throughput | Goodput |
|---|---|---|
| Simulation Results | 719.65 | 543.09 |
| Analytical Results-S | 722.63 | 545.38 |
| Analytical Results-Q | 748.48 | 558.10 |
| ideal Transport | - | 907.18 |

Key achievements

- A good match between the analytical model results and the detailed system simulation results
- The FC and CC investigation and analysis can be done **faster** using the analytical model along with the fast queuing simulator compared to detailed system simulator
  - Detailed system simulator: **order of days**
  - Analytical model: **order of minutes**

# Conclusion

- Detailed HSPA system simulator has been implemented, tested, validated and used for the performance evaluation.
- TNL credit-based adaptive flow control and congestion algorithms have been implemented tested, validated and used for end-to-end performance analysis.
  - Overall network performance can be significantly improved by **reducing burstiness** over the transport network, **optimising transport utilisation** and effectively **minimising congestion** in the transport network
  - FC and CC algorithms provides **guaranteed end-user QoS** while achieving a **optimum end-user performance**
- Two analytical models has been implemented, tested, validated and evaluated the performance.
  - A **Markov model** for modelling **congestion control** functionality
  - A **joint Markov model** for modelling **FC** and **CC** functionalities

# Conclusion

- There is a good match between analytical model results and the detailed system simulation results.
- A complete faster alternative solution to the timing consuming detailed system simulator can be provided by the analytical mode along with the fast queuing for TNL feature analysis.
- Detailed LTE system simulator implemented, tested, validated and performance analysed.
  - In addition to general protocol implementation, MAC scheduler and transport QoS packet scheduler have been implemented
  - Effects of transport congestion for network and end-user performance have been studied and analysed

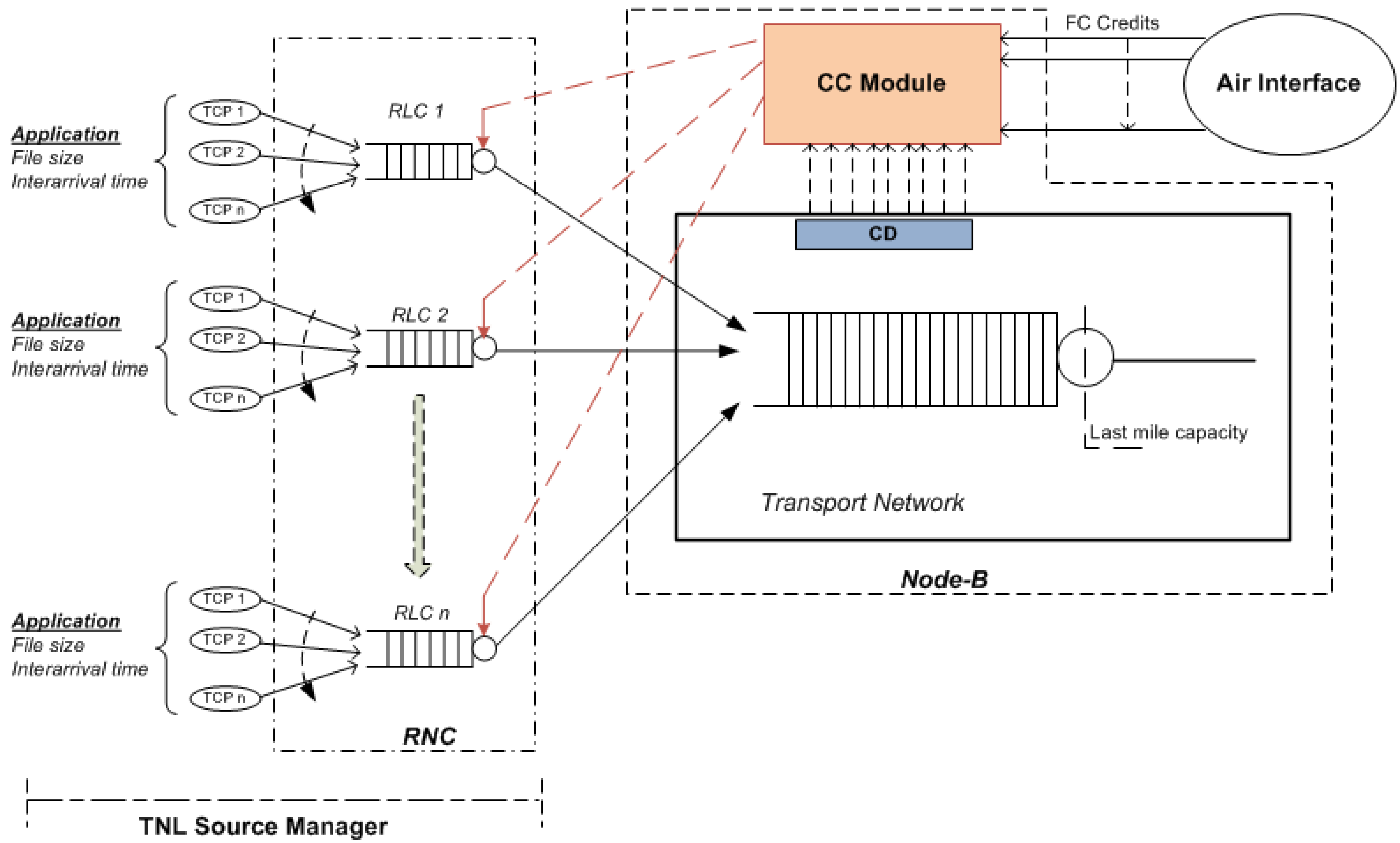
# Outlook

- Proper flow control and congestion control schemes are needed to be proposed and implemented in the LTE UTRAN in order to protect transport packet losses due to congestion
  - UL congestion control and load balancing  for non-GBR bearers
  - DL congestion handling mainly for non-GBR bearers
  - Effective admission control mechanism for GBR bearers
- There is a clear requirement of cross layer functionalities between Radio MAC scheduler and transport scheduler for effective QoS management

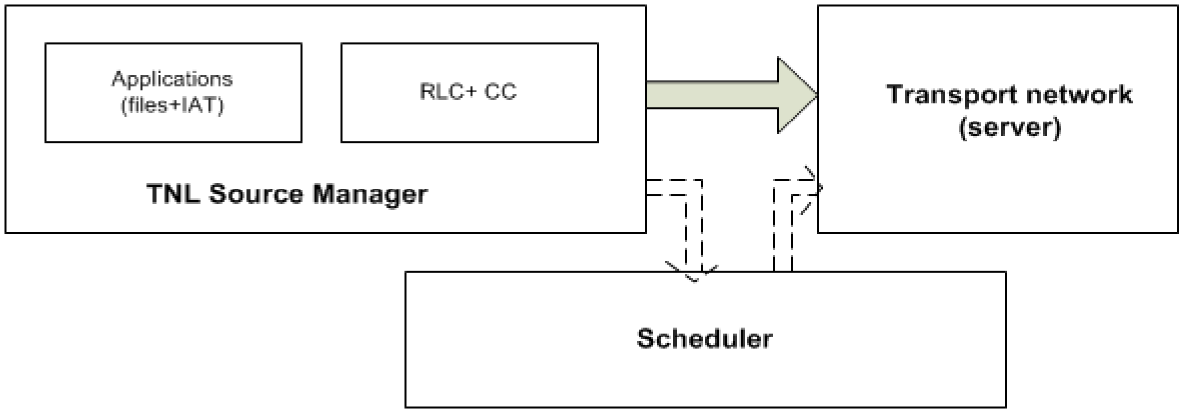
# Thank you very much!

Any Questions?

# Design overview of the queuing simulator



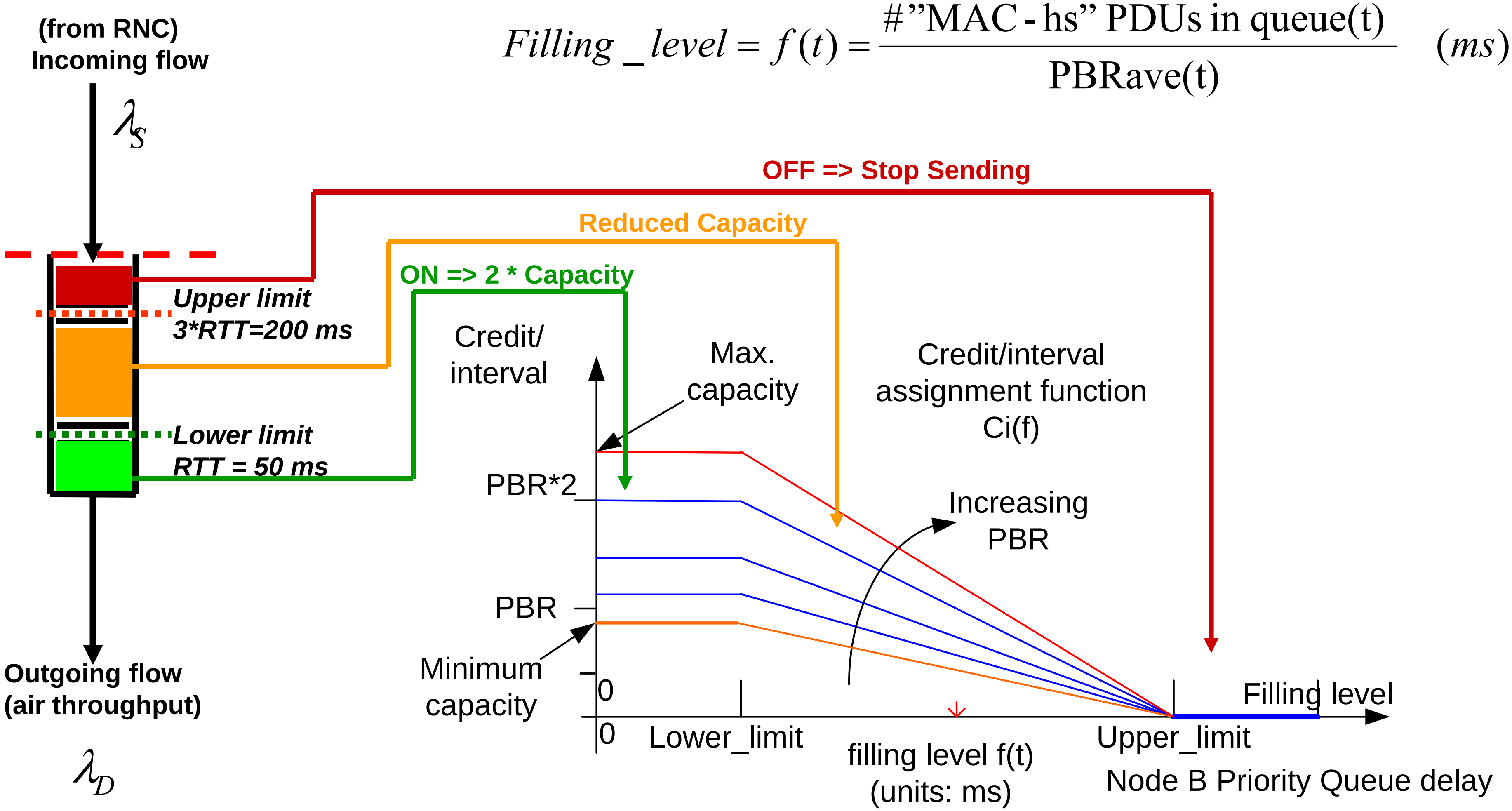
# Fast queuing simulator



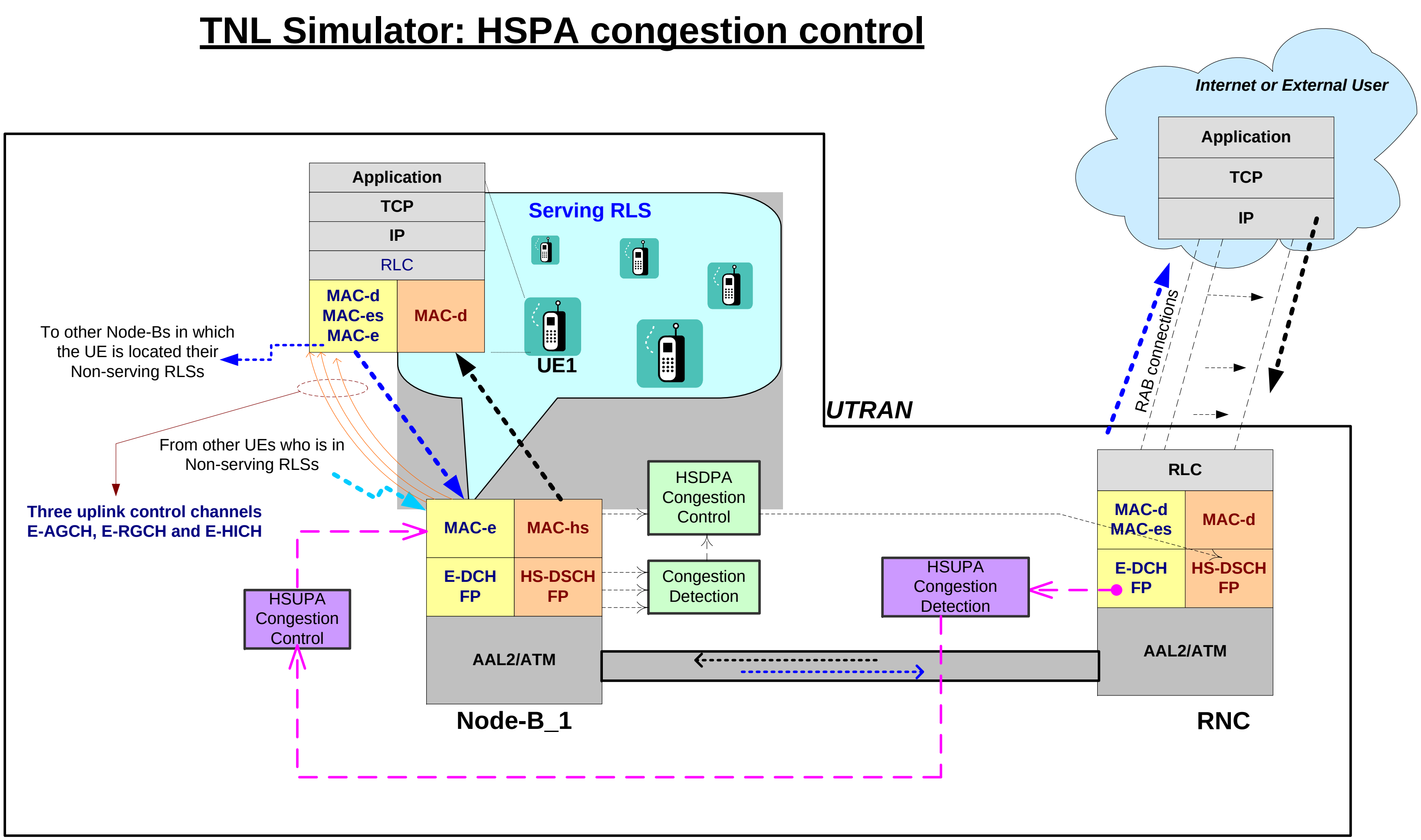

- A fast queuing simulator is implementation using CNCL library
- Key assumptions and simplifications
  - Traffic sources are modelled without complex TCP protocol functionality
  - Transport loss ratio set to the maximum value 1% and losses are uniformly distributed. (RLC able to recover the loss before TCP notices)
  - The CI arrival process assumed as a Poisson arrival

# FC Queue management

$$Filling\_level = f(t) = \frac{\#\text{"MAC-hs" PDUs in queue(t)}}{\text{PBRave(t)}} \quad (ms)$$



# Flow control and congestion control cont.



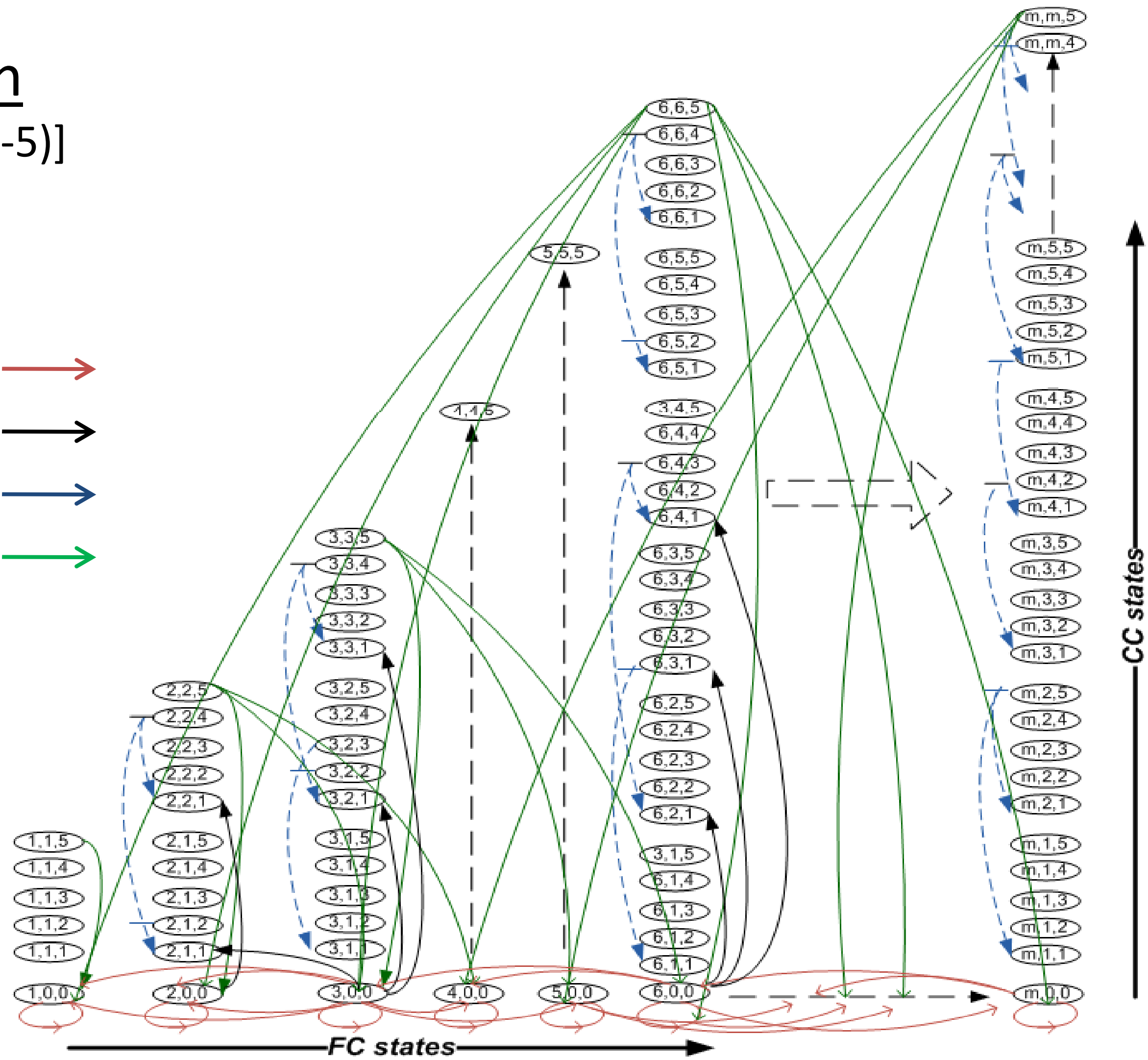
# Joint Markov chain: state diagram

## State representation

[i,j,k] = [FC, CC, Steps(1-5)]

## State transition

- FC to FC transitions →
- FC to CC transitions →
- CC to CC transitions →
- CC to FC transitions →



# Markov model: states

- Each state is identified by three non-negative integers, $[i, j, k]$
  - Bit rate level in the FC state, $i$ $[i = 1, 2, 3, \dots m]$
  - Bit rate level in the CC state, $j$ $[j = 1, 2, 3, \dots m]$
    - "*j=0*" indicates the state within FC state
  - Time step in CC state, $k$ $[k = 1, 2, 3, \dots 5]$
    - Again "*k=0*" indicates the state within FC state

- Number of states in Markov model
  - Total number of FC states = $m$
  - Total number of CC states = $\frac{m \cdot (m+1) \cdot 5}{2}$, where CC state finite sequences 5,10,15,20.......,5$m$ => $(5n)_{n=1}^{m}$
  - The total number of FC states and CC states: $m + \frac{m \cdot (m+1) \cdot 5}{2}$

*For example, if m is 48 (eff_BW/step = 2.0*10$^6$*0.8/33.6*10$^3$), then the total number of states is 5928.*

# Simulation results analysis

- Replication mean calculation

$$\text{Replication 1}: Y_1, Y_2, Y_3, \ldots Y_m \; ----> \overline{Y}_1$$

$$\text{Replication 2}: Y_{m+1}, Y_{m+2}, Y_{m+3}, \ldots Y_{2m} \; ----> \overline{Y}_2$$

$$\text{Replication 3}: Y_{2m+1}, Y_{2m+2}, Y_{2m+3}, \ldots Y_{3m} \; ----> \overline{Y}_3$$

..

$$\text{Replication n}: Y_{(n-1)m+1}, Y_{(n-1)m+2}, Y_{(n-1)m+3}, \ldots Y_{nm} \; ----> \overline{Y}_n$$

$$\text{Mean}: \; \overline{Y} = \frac{1}{n}\sum_{i=1}^{n} \overline{Y}_i$$

$$\text{Variance}: \; V = \frac{1}{n-1}\sum_{i=1}^{n}\left(\overline{Y} - \overline{Y}_i\right)^2$$

$$\text{Confidence interval} \; = \overline{Y} \pm (t_{\alpha/2, n-1} \times \sqrt{\tfrac{V}{n}})$$

$$\text{where } 100(1-\alpha)\% \text{ CI}$$

where $t_{\alpha/2,\, n-1}$ is taken from Student t-distribution. "$n-1$" is the degree of freedom and 1-α is the confidence level.

- Statistical evaluation

| *Replications, i* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* |
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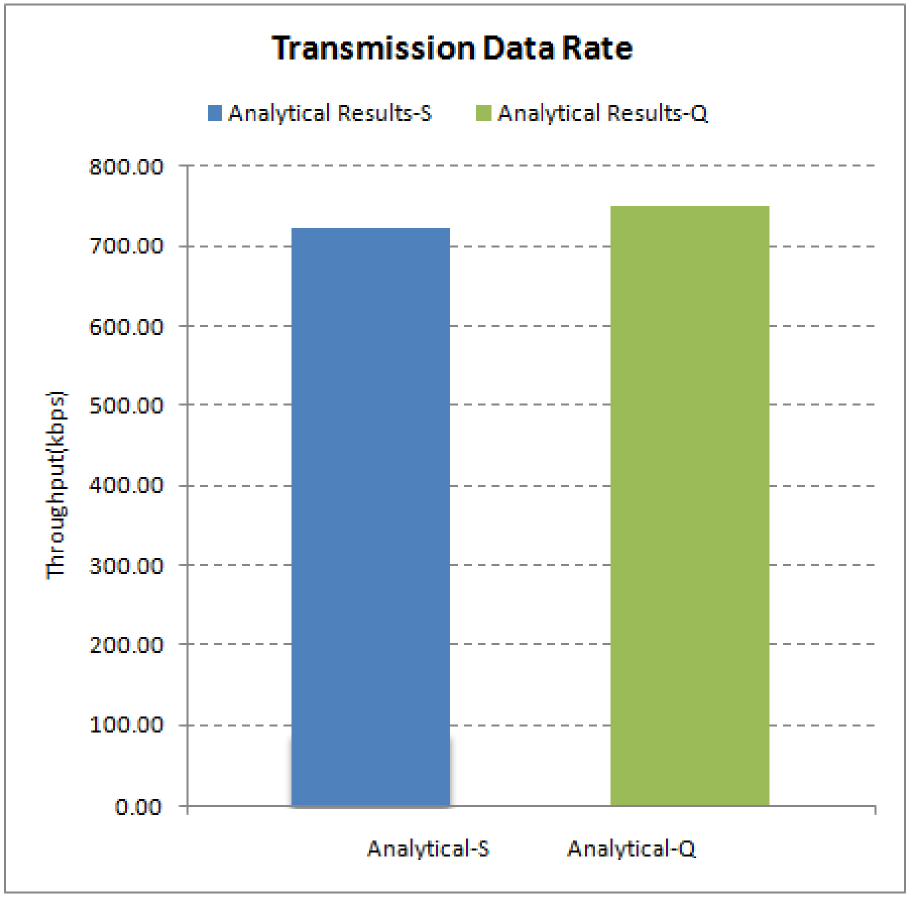
- Mean = 719.60 kbit/sec
- Standard deviation = 21.13 kbit/sec
- 95%confidence interval = [713.05 kbit/sec– 726.16 kbit/sec]

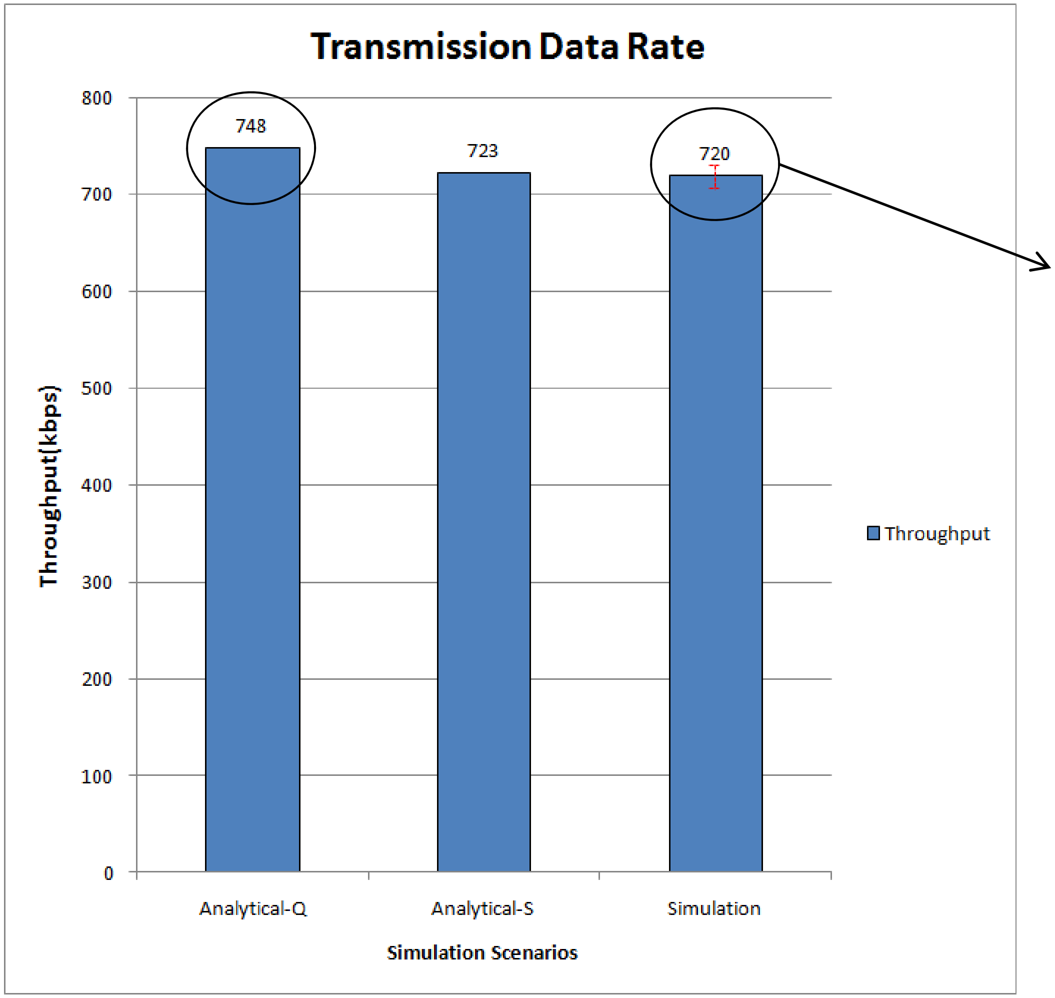
# Analytical results

- Analytical model-Q
  - CI trace from the fast queuing simulator
- Analytical model-S
  - CI trace from the detailed system simulator

| | Analytical-S | Analytical-Q |
|---|---|---|
| Probability of no CI arrival within a single step, $q_0$ | 95.83% | 94.74% |



# Results comparison




Simulation

*Mean throughput = 719.65 kbit/sec*

*95% CI (713.05 kbps, 726.16 kbit/sec)*

*There are many issues for this difference during this analysis*

- *Fast queuing simulator analysis had higher number of RLC retransmissions compared to detailed system simulator and it leads to a higher throughput for fast queuing simulator (loss probability of the detailed system simulator is 0.41% whereas it is 1% for the fast queuing simulator. Additional overhead is ~6kbit/sec.)*
- *There are other effects which cannot be quantified as above such as*
  - *Losses are uniformly distributed*
  - *Effect of TCP slow start etc..*
- *And all other protocol effects and assumptions*

➡ Goodput comparison provide more close agreement

# Joint Markov chain

## State representation

three non-negative integers, $[i, j, k]$

- Bit rate level in FC state, $i$ $[i = 1, 2, 3, \ldots m]$
- Bit rate level in CC state, $j$ $[j = 1, 2, 3, \ldots m]$
- Time steps in CC state, $k$ $[k = 1, 2, 3, \ldots 5]$

## The number of states

The total number of FC states and CC states $= m + \dfrac{m \cdot (m+1) \cdot 5}{2}$

## State transition

- FC to FC transitions (red arrow)
- FC to CC transitions (black arrow)
- CC to CC transitions (blue arrow)
- CC to FC transitions (green arrow)

## Input Parameters

Stationary FC state prob. matrix,

$PBRm = \left[ pbr_j \right]_{1 \times m}$ where $j = 1 \ldots m$

CI arrival prob. matrix,

$A_{ci} = [q_i]_{1 \times (1 + d_{max})}$ where

$q_i = \Pr[\text{exactly } i \text{ CI signals during } \Delta T]$;

$i = 0 \cdots d_{max}$

**State diagram**