Resource Management in Mobile Networks

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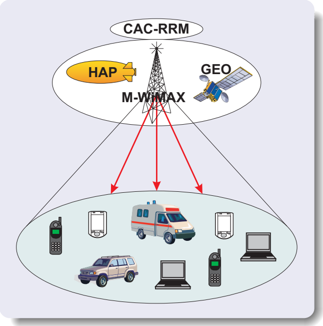
Research Area

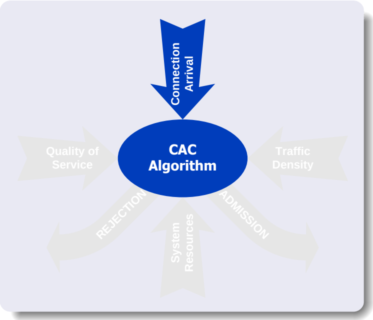
- Development of techniques for increasing the mobile networks' capacity while satisfying the requested Quality-of-Service (QoS)
- Incorporating the configuration and variations of the Physical Layer into the decision criteria of the Resource Management mechanisms
- Connection Admission Control: Precise computation of the connections' needs in bandwidth
- Radio Resource Management: Efficient allocation of the available spectrum

- Mobile Networks
  - M-WiMAX
  - HAP
  - GEO



Connection Admission Control - CAC

- Congestion prevention mechanism
- Acceptance/Rejection of new connections based on the anticipated resource availability



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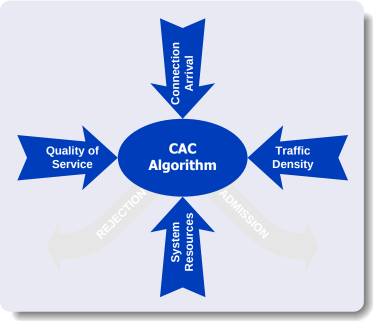

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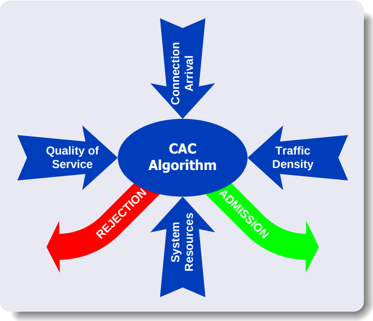

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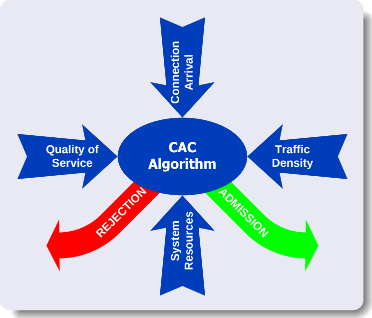


- CAC policy is formulated as a tradeoff between:

Exploitation of the available resources

- Lenient acceptance criteria
- High likelihood of congestion phenomena

Guaranteed Quality-of-Service

- Strict acceptance criteria
- Low revenue for the operator

Connection Admission Control - CAC

- Inefficient CAC Implementations
- Inability to perform accurate predictions for the system's future states

- Stochastic nature of the connections' arrival-termination process
- Variation of data generation rate at Application Layer
- Dependence of a connection's bandwidth requirements upon the Physical Layer performance

Radio Resource Management - RRM

- RRM routines follow in time the execution of the CAC mechanism
    - Execution upon already admitted connections
- Dynamic allocation of the available resources among the active connections
    - Spectrum of the physical medium
    - Transmission power

Radio Resource Management - RRM

- 2 cases of RRM triggering

Under conditions of congestion

- Failure of the CAC mechanism - Congestion Prevention
- Allocation of the insufficient resources among the competing connections, according to several prioritization criteria
  - Maximum utilization of the network's resources - Maximum operator's revenue
  - Connections' QoS requirements (sustainable datarate, delay, jitter tolerance)
  - Fairness
  - Class priority

Under conditions of normal operation

- Resource saving for servicing additional connections - Capacity increase

WiMAX Family of Standards

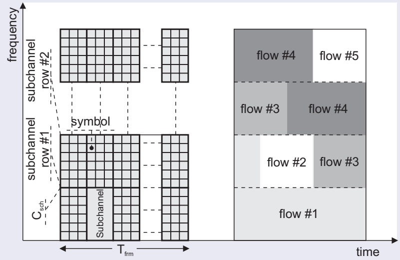
Worldwide Interoperability for Microwave Access

- IEEE 802-16d - 2004
    - Current standard for Fixed Wireless MAN - Fixed-WiMAX
    - Medium Access: OFDM
    - Frequency Band: 2-11GHz
    - NLOS - Non Line-Of-Sight communication
    - Maximum coverage 50km
    - Average Datarate: 75Mbps
    - Supports mesh architecture
- IEEE 802.16e - 2005
    - Current standard for Mobile Wireless MAN - M(obile) WiMAX
    - Supports mobility
    - Medium Access: Scalable-OFDMA
    - Hybrid Automatic Repeat-reQuest (HARQ)
    - Adaptive Antenna Systems (AAS) and MIMO technology
    - Turbo Coding and Low-Density Parity Check (LDPC)
    - One extra QoS class for VoIP applications

M-WiMAX - Key Functions

Physical Layer - OFDMA

- Division of the aggregate bandwidth into C_{tot} orthogonal and partially overlapping subcarriers
  - C_{dat} subcarriers for application data transmission and the rest for signalling
- Division of the timeline into successive timeframes of duration T_{frm}
  - Segmentation of each timeframe into L_{tot} timeslots
- Minimum spectrum allocation unit: subchannel
  - 2-dimension combination of C_{sch} subcarriers and L_{sch} timeslots



$$SR_{max} = \frac{C_{dat} \cdot L_{tot}}{T_{frm}} \text{ symbols/sec}$$

M-WiMAX - Key Functions

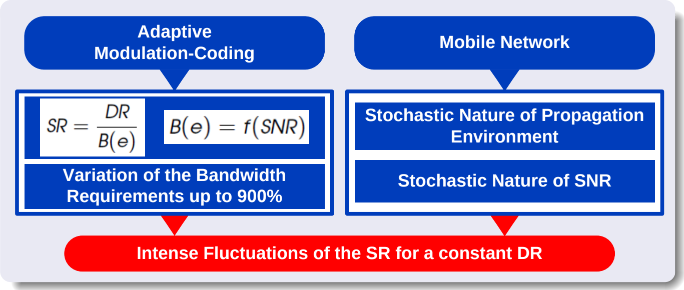
Physical Layer - Adaptive Modulation-Coding (AMD)

- The Modulation-Coding combination is chosen as a function of the SNR
- 7 Modulation-Coding Levels (MCL), $e \in \mathbf{E} \equiv \{1, \ldots, 7\}$
  - $SNR_{thr,e}$: Threshold SNR for MCL$=e$
  - $B(e)$: Data bits per symbol (Data Link Layer data-stream, before Physical Layer coding), for MCL$=e$
  - Required symbol-rate for achieving datarate DR bps:

$$SR = \frac{DR}{B(e)} \text{ symbols/sec}$$

MCL (e)	**Modulation & Coding**	**Data Bits per Symbol** $(B(e))$	**Required SNR** $(SNR_{thr,e}$ **in dBs**$)$
0	-	-	-
1	BPSK & 1/2	0,5	6,4
2	QPSK & 1/2	1	9,4
3	QPSK & 3/4	1,5	11,2
4	16QAM & 1/2	2	16,4
5	16QAM & 3/4	3	18,2
6	64QAM & 2/3	4	22,7
7	64QAM & 3/4	4,5	24,4

CAC Failure at M-WiMAX systems



- Degraded effectiveness of CAC's implementations
  - Difficulties in performing safe predictions of the connections' future bandwidth requirements
  - Unjustifiable increase in Blocking Probability
  - Frequent occurrence of congestion phenomena

Need for a precise estimation of the evolution of the aggregate Symbol Rate along time

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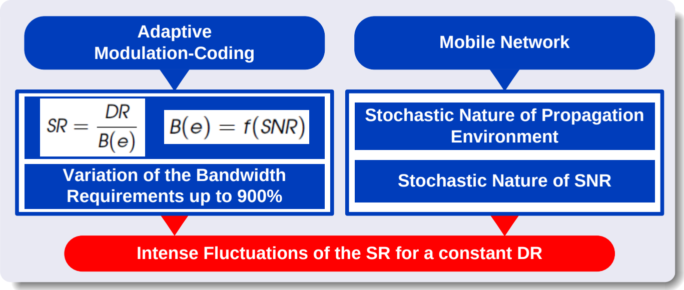

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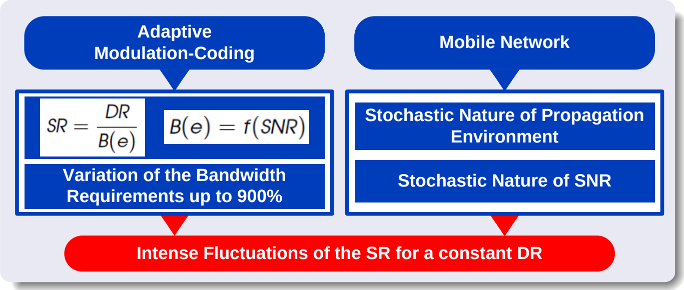

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Aggregate Symbol Rate vs. MCL Distribution

- Mean value of the aggregate symbol transmission rate

$$SR_{\mathbf{H},av} = \left\{ P[MCL = 0] \cdot 0 + \sum_{e=1}^{7} \frac{P[MCL = e]}{B(e)} \right\} \cdot \sum_{h=1}^{H} DR_h$$

- Calculation of the probability that a connections resides within any of the 7 available MCLs: $P[MCL = e]$
  - Average connections' percentage per MCL

$$P[MCL = e] = \begin{cases} P[SNR < SNR_{thr,e+1}] & , e = 0 \\ P[SNR_{thr,e} \leq SNR < SNR_{thr,e+1}] & , 1 \leq e \leq 6 \\ P[SNR \geq SNR_{thr,e}] & , e = 7 \end{cases}$$

$$\left\{ \begin{array}{l} SNR = S_{Tx} - A_{ag} - N_0 \\ L_e = S_{Tx} - SNR_{thr,e} - N_0 \end{array} \right\}$$

$$P[MCL = e] = \begin{cases} P[A_{ag} > L_{e+1}] & , e = 0 \\ P[L_{e+1} < A_{ag} \leq L_e] & , 1 \leq e \leq 6 \\ P[A_{ag} \leq L_e] & , e = 7 \end{cases}$$

The Three Components of Total Propagation Losses

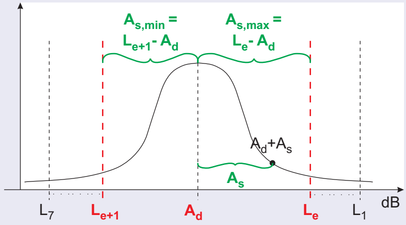
- Splitting the aggregate losses A_{ag} into its comprising components
  - A_d: Free space losses
    - Function of the distance and the frequency: $A_d = f(d, f)$
    - The predominant factor of the total attenuation - Large coverage area of M-WiMAX (macrocell)
    - Very slow variations against time: 1dB for distance change of $\approx 6\%$
  - A_s: Shadowing
    - Normal distribution with $\overline{A_s} = 0dB$ and $\sigma_{A_s} \in$ [6dB, 12dB]
    - Smooth variations against time: High correlation between successive timeframes
  - A_f: Fast Fading due to multiple paths
    - Very low correlation between successive timeframes
    - Mitigation of the A_f fluctuations through extensive sampling

Distribution of the Total Propagation Losses

- The distribution of MCL is almost exclusively dictated by the evolution of A_d and A_s against time

$$A_{ag} = A_d + A_s$$

Distribution of A_{ag}



$$P[L_{e+1} < A_{ag} \leq L_e] = \int_{A_{dm}}^{A_{dM}} P[A_d = A_{d_x}] \cdot P[L_{e+1} - A_{d_x} < A_s \leq L_e - A_{d_x}] dA_{d_x}$$

$$= \int_{A_{dm}}^{A_{dM}} P[A_d = A_{d_x}] \left(\int_{L_{e+1} - A_{d_x}}^{L_e - A_{d_x}} pdf(A_s) dA_s \right) dA_{d_x}$$

Distribution of the Total Propagation Losses

- Shadowing losses A_s follow normal distribution
  - The *cumulative distribution function* cannot be analytically computed as a function of its limit
  - The continuous space of A_d ($A_d \in [A_{d_m}, A_{d_M}]$) is quantized with step $a \longrightarrow 0$ into $b \longrightarrow \infty$ discrete, successive values

$$A_{d_x} \in \{A_{d_m}, A_{d_m} + a, \ldots, A_{d_m} + (b-2)a, A_{d_M}\} ,x = \{1, \ldots, b\}$$

- The probability that the total losses fall within a given space

$$P[L_{e+1} < A_{ag} \leq L_e] = \sum_{x=1}^{b} \left\{ P[A_d = A_{d_x}] \left(\int_{L_{e+1}-A_{d_x}}^{L_e - A_{d_x}} pdf(A_s) dA_s \right) \right\}$$

Distribution of the Total Propagation Losses

- A_d: Discrete variable

$$P[A_d = A_{d_x}] = P[A_d \le A_{d_x}] - P[A_d \le A_{d_x}^-]$$

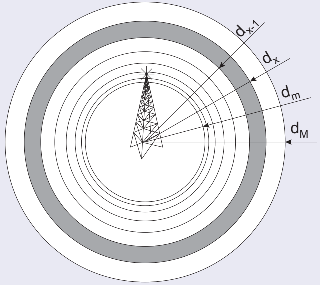
- For quantization step $a = (A_{d_x} - A_{d_{x-1}}) \longrightarrow 0$

$$P[A_d = A_{d_x}] = P[A_d \le A_{d_x}] - P[A_d \le A_{d_{x-1}}]$$

- A_d: Genuinely ascending function of the distance, with $A_d = f(d)$

$$P[A_d \le A_{d_x}] = P[d \le d_x] \ , d_x = f^{-1}(A_{d_x}) \in [d_m, d_M]$$

Split of the coverage area into concentric circles



- Uniform spatial distribution of the traffic sources

$$P[A_d = A_{d_x}] = \frac{(f^{-1}(A_{d_x}))^2 - (f^{-1}(A_{d_{x-1}}))^2}{d_M^2 - d_m^2}$$

Calibration Routine

- The reference model is built upon statistical analysis (*pdf*, mean rate, variation)
- Deviation of the average operational state of the real system from the reference model

Anticipated mean SNR value according to the reference model

$$\overline{SNR_{st}} = S_{Tx} - \overline{A_d} - \overline{A_s} - N_0$$

Measured mean SNR rate at the operating network

$$\overline{SNR_{mr}}$$

Calibration Factor

$$V = \overline{SNR_{st}} - \overline{SNR_{mr}}$$

- Finally, the MCL distribution ($P[MCL = e]$) is calculated for

$$L'_e = L_e - V, \forall e \in \{1, \ldots, 7\}$$

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Anticipated Behaviour Per Connection

- Estimation of the symbol transmission rate for every connection $h \in \{1, \ldots, H\}$ separately

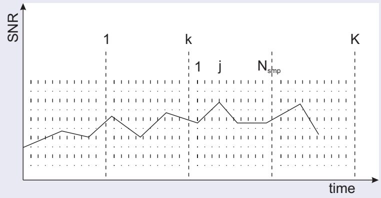
$$SR_{\mathbf{H},pr} = \sum_{h=1}^{H} SR_h = \sum_{h=1}^{H} \frac{DR_h}{B(MCL_{h,pr})}$$

- Exploitation of the available SNR sampling
- Short-term prediction of the MCL per connection
  - Filtering mechanism for suppressing any transit phenomena
    - Impact of shadowing (A_s) and fast fading (A_f)
    - Abrupt changes of A_d due to temporal distance fluctuations in regard to the Base Station
  - Isolation of the primary SNR pattern
    - Dependent solely on the distance evolution against time

Filtering Routine of the SNR samples

- Monitoring of every connection $h \in \mathbf{H}$ at consecutive timeframes T_{frm}: $1_h, \ldots, k_h, \ldots, K_h$
- SNR sampling with period $T_{smp} < T_{frm}$
- $N_{smp} = T_{frm}/T_{smp}$ sample per timeframe
- Calculation of the mean SNR for every timeframe k_h:

SNR Sampling



$$SNR_{h,k,av} = \frac{1}{J_h + 1} \cdot \left\{ SNR_{h,k-1,av} + \sum_{j=1}^{J_h} SNR_{h,k,j} \right\}$$

- Discarding all samples outside the space $SN_{h,k,av} \pm Q\%$

$$SNR_{h,k,j} \in [SNR_{h,k,av} - Q\%, SNR_{h,k,av} + Q\%]$$

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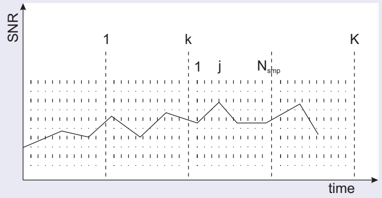

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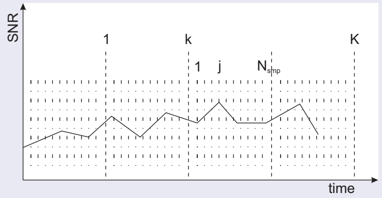

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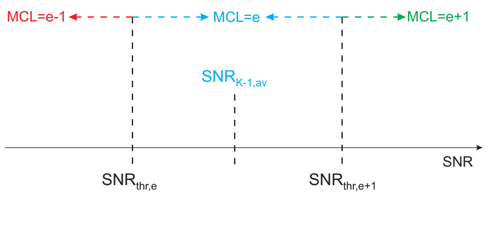

$$\left\{ \begin{array}{c} SNR_{h,K,av} > SNR_{h,K-1,av} \\ SNR_{h,K,av} > SNR_{thr,(e_h+1)} - X\% \end{array} \right\} \Rightarrow MCL_{h,pr} = e_h + 1$$

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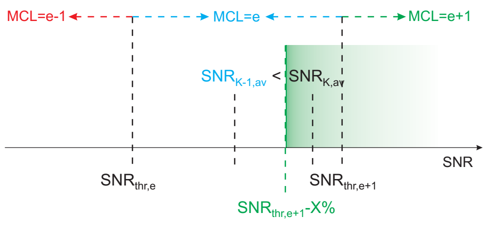

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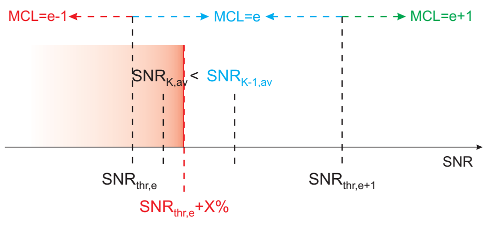

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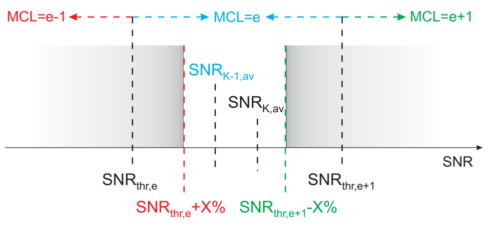

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The CAC algorithm

- New connection arrival c with requested datarate DR_c
  - Proposed CAC according to the *Average System Behaviour*

CAC_A

$$SR_{\mathbf{H},av} + \frac{DR_c}{B(MCL_c)} \leq SR_{max}$$

  - Proposed CAC according to the *Per Connection Behaviour*

CAC_B

$$SR_{\mathbf{H},pr} + \frac{DR_c}{B(MCL_c)} \leq SR_{max}$$

  - Proposed Hybrid CAC

CAC_{HY}

$$\min\{SR_{\mathbf{H},av}, SR_{\mathbf{H},pr}\} + \frac{DR_c}{B(MCL_c)} \leq SR_{max}$$

Evaluation

Evaluation Criteria

- Evaluation Criteria
  - Blocking Probability - *BP*

$$BP = \frac{\text{number of rejected connections}}{\text{total number of arrivals}}$$

  - Mean Satisfaction Factor - *MSF*

$$SF_h = E\left[\frac{DR_h(t)}{MRTR_g}\right], \forall t \in T_{tot,h} \qquad MSF = \frac{1}{H} \cdot \sum_{h=1}^{H} SF_h$$

Optimum Performance CAC

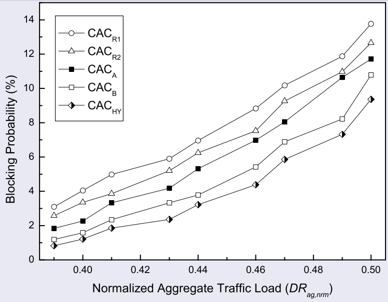
$$BP \longrightarrow 0 \cap MSF \geq 1$$

- CAC algorithms of reference
  - CAC_{R1}: Admission/Rejection based on the instantaneous MCL
  - CAC_{R2}: Admission/Rejection based on the last N SNR samples

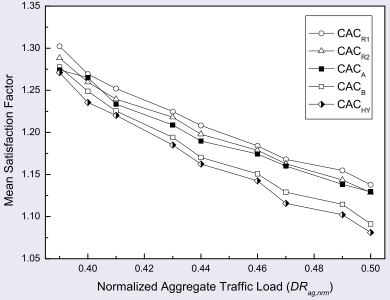
Evaluation

Comparative Study - Simulation Results

Blocking Probability - *BP*



Mean Satisfaction Factor - *MSF*



- *BP* decrease up to 50%
  - Corresponding increase of the spectrum utilization
- *MSF* remains over the limit of 100%
  - Guarantee of the requested QoS

Bandwidth Allocation under Transmission Power Limitations

- SNR: Reversely proportional to the number of occupied subcarriers C

$$(SNR)_{dB} = \left(\frac{S_{Tx,max}}{C}\right)_{dBm} - (A_{ag})_{dB} - (N_0)_{dBm} \implies \frac{dSNR}{dC} < 0$$

- Data bits per symbol $B(MCL)$: Descending function of C

$$\frac{dB(MCL(C))}{dC} \leq 0$$

- Additional subcarrier allocation does not necessarily causes proportional datarate DR increase

$$DR(C) = \frac{C \cdot L_{tot} \cdot B(MCL(C))}{T_{frm}}$$

- Non-linear relationship between SR (spectrum consumption) and DR (QoS)
- Optimum C definition:

$$SR \downarrow \ \cap \ DR \longrightarrow DR_{req}$$

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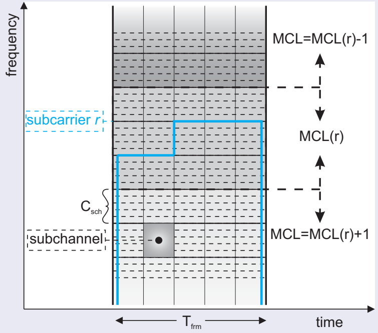
Proposed RRM Algorithm - RRM_{UL}

Number of subcarriers $DR = DR_{req}$: $C = r$

- $r = min\{C : DR(C) \geq DR_{req}\}$
- $D(r) = DR_{req} \cdot T_{frm}$ $S(r) = \frac{D(r)}{B(MCL(r))}$

OFDMA timeframe



Optimum number of subcarriers for spectrum saving

1^{st} timeframe: $C = m$

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k next timeframes: $C = M$

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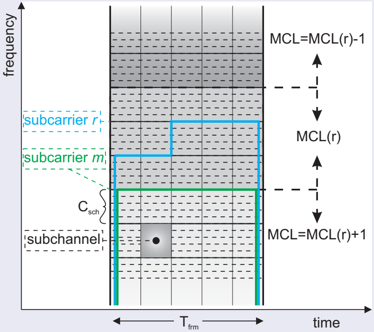

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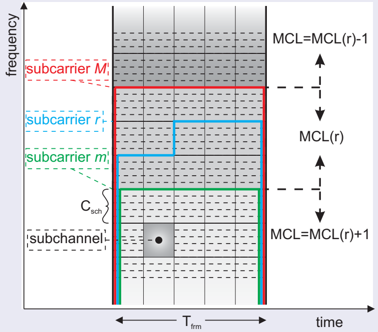

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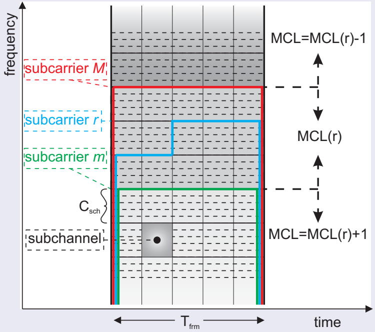

Optimum number of subcarriers for spectrum saving

- *DR* degradation at the 1st timeframe
- Full *DR* compensation during the *k* next timeframes
- 1st frame: Symbol gain higher than bits losses - Increase in bits/symbol
- *k* frames: Symbol loss proportional to bits gain - Constant bits/symbol
- Totally for $k + 1$ frames: Spectrum saving without QoS degradation

Theoretical Proof of RRM_{UL} Efficiency

- Total gain in bits over $k+1$ timeframes:

$$GD_{agg}(k+1) = (D(m) - D(r)) + k \cdot (D(M) - D(r))$$

- Total gain in symbols over $k+1$ timeframes:

$$GS_{agg}(k+1) = (S(r) - S(m)) + k \cdot (S(r) - S(M))$$

- $GD_{agg}(k+1) = 0$. Hence

$$GS_{agg}(k+1) = m \cdot \left(\frac{B(MCL(m))}{B(MCL(r))} - 1 \right) \cdot L_{tot}$$

- Spectrum saving whenever the proposed algorithm is executed

$$B(MCL(m)) > B(MCL(r)) \Rightarrow GS_{agg}(k+1) > 0$$

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Conditions of Maximum Efficiency for RRM_{UL}

- Conditions of definition for m

$$\exists m \Leftrightarrow MCL(r) < MCL(C_{sch})$$

Doubling C from C_{sch} to $2 \cdot C_{sch} \Rightarrow$

Decrease of SNR by 3dB $\Rightarrow$

Degradation by 1 MCL $\forall SNR \notin [SNR_{thr,4} - 3, SNR_{thr,4}] \cap [SNR_{thr,7} + 3, \infty]$

$$\exists m \Leftrightarrow DR_{req} > DR(C_{sch}) \Leftrightarrow r > C_{sch}$$

MCL (e)	Maximum datarate for $C = C_{sch}$ ($DR_{max,e}$ in kbps)
1	58,8
2	117,6
3	176,4
4	235,2
5	352,8
6	470,4
7	529,2

For $DR_{req} \in [DR_{max,e}, DR_{max,e+1}]$

$$\exists m \Leftrightarrow SNR < SNR_{thr,e+1}$$

$$P[\exists m] \uparrow \Leftrightarrow SNR \downarrow \cap DR_{req} \uparrow$$

Conditions of Maximum Efficiency for RRM_{UL}

- Conditions of definition for M

$$\exists M \Leftrightarrow DR_{req} \text{ is satisfied} \Leftrightarrow \exists r$$

$$P[\exists M] \uparrow \Leftrightarrow SNR \uparrow \cap DR_{req} \downarrow$$

- Parallel satisfaction of both m and M conditions

$$P[\exists m \cap \exists M] \uparrow$$

$$\Leftrightarrow$$

$$DR_{req} \longrightarrow DR^{+}_{max,e}, \forall e \in \mathbf{E}$$

Bandwidth Saving

- $GS_h(t)$: Percentage gain in symbols per timeframe using RRM_{UL}

$$GS_h(t) = \frac{S_{bas}(t) - S_{pro}(t)}{S_{bas}(t)}$$

- BGR: Mean bandwidth saving for all connections

$$BGR = \frac{1}{H} \cdot \sum_{h=1}^{G} \{[GS_h(t)]\}$$

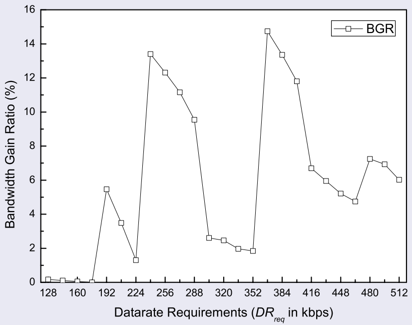
- Desirable behaviour

$$BGR \uparrow$$

- Iterative saw-like pattern, with peaks at

$$DR_{req} \longrightarrow DR^{+}_{max,e}$$

Bandwidth Gain Ratio - *BGR*



Quality of Service

Mean Datarate

- $VD_h(t)$: Percentage deviation of the number of forwarded bits per timeframe using RRM_{UL}

$$VD_h(t) = \frac{D_{pro}(t) - D_{req}(t)}{D_{req}(t)}$$

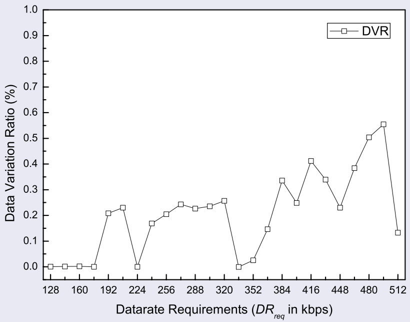
- DVR: Mean deviation of the volume of forwarded data for all connections

$$DVR = \frac{1}{H} \cdot \sum_{h=1}^{G} \{[VD_h(t)]\}$$

- Desirable behaviour

$$DVR \longrightarrow 0$$

Data Variation Ratio - *DVR*

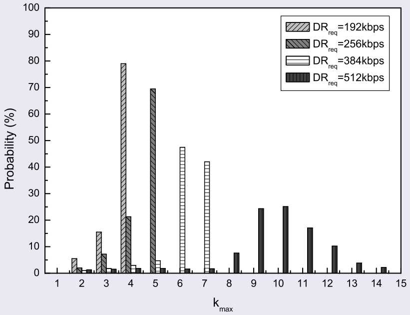


Quality of Service

Delay

- Distribution of k_{max}
- $k_{max,h}$: Maximum value of k for the whole duration of connection h
- At every RRM_{UL} execution, datarate remains degraded for k timeframes
- The duration of $k+1$ timeframes should not surpass the maximum delay boundary of the forwarded application
- Evaluation criterion only for real-time connections

Distribution of k_{max}



Resource Management in Mobile Networks

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