Multi-user Video Streaming in Cognitive Radio Networks:

When QoS Meets Spectrum

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Outline

- Background and motivation
- Overview
  - Technical challenges and existing solutions
- Case studies
  - Video multicast over cellular CR networks
  - Muti-user video streaming over multihop CR networks
  - Multi-user video streaming in a cellular CR network
- Open problems
- Conclusions

Fundamental Changes in Wireless Data

- Top: Sept. 17, 2008 Qiantang River Tide
- Bottom: Sept. 22, 2013 Qiantang River Tide WaveSome
- Some fundamental changes have happened …

http://news.shouyou.com/news/01172014/123507405.shtml

Similar Things Happened in the Europe and the US

http://www.businessinsider.com

The Smartphone Revolution (contd.)

- The iPhone 5s is 15,625 times more powerful than the computer used for the first moon landing
    - iPhone CPU: 625 times more transistors than a 1995 Pentium CPU
- Every single item in this 1990 Circuit City ad are now replaced by the smartphone
- Apple: 75 Billion app downloads
    - 12 apps on a smartphone on average
- The average user check their phone 110 times a day
    - 12% used it in the shower

http://www.slideshare.net/GoCanvas/15-facts-37654260

More Mobile Devices and Apps …

- More mobile device on earth than people
- They are data hungry …
- Year 2000: 1 Exabyte (the entire Internet)
  Year 2013: 18 Exabyte (mobile data)
  Year 2018: 15 Exabyte (per month)

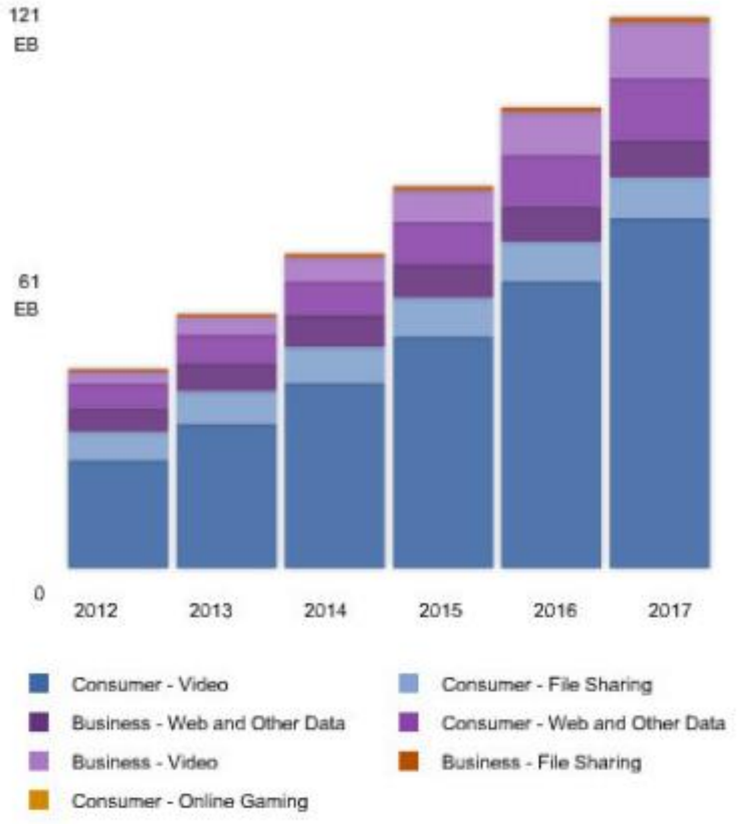
* Monthly basic mobile phone data traffic

Source: Cisco VNI Mobile, 2011

http://www.businessinsider.com/

… and the Cellular Data Crisis

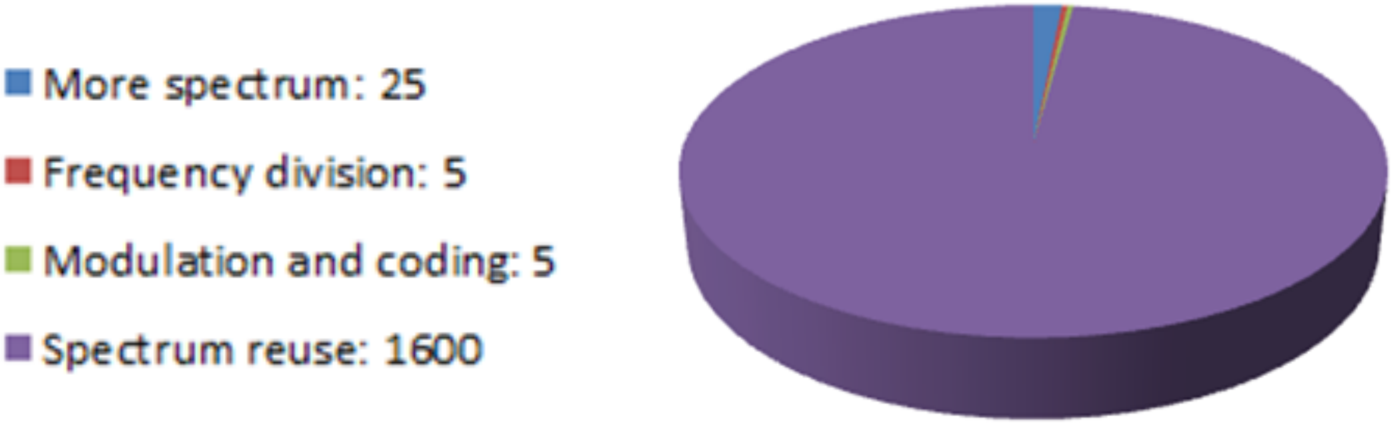
- A 1000-fold mobile data traffic growth since 2010
- By 2018, there will be nearly five billion global mobile users, up from more than four billion in 2013
- Internet video
  - 40% of consumer Internet traffic
  - 62% in 2015
- **Mobile video** is already half of the overall mobile data traffic, and …
  - … will be 69% of the mobile data traffic by 2018



*Cisco VNI, Feb 2014

“Moore’s Law” for Wireless

- According to *Martin Cooper* (one of the pinions of cellular telephony)
  - The wireless throughput has doubled every 30 months over a period of 104 years
  - A million-fold increase since 1957
- A breakdown of the gain



Implications

- Convergence of wireless computer networks and cellular networks
- The capacity of existing and future wireless networks will be greatly stressed
- Quality of Service (QoS)/Quality of Experience (QoE) in wireless networks
  - Traffic/spectrum modeling, queueing, network calculus, effective bandwidth, effective capacity
    - ➔ will come back
- Hot-spots/flash crowd: interference becomes the limiting factor
  - Interference exploitation/mitigation/management
- Coverage for sparse, rural areas
- Green communications and networking
  - In addition to mobile devices, BS power consumption should be considered
- Wireless security and privacy
  - Physical layer security, location based service, …
- Anywhere, anyone, anytime …
  - … any scale, any thing, any app, any QoS/QoE, any price

Towards the 5G Wireless

- Spectrum expansion
  - TV whitespace: 572—698 MHz: IEEE 802.22Wireless RAN
  - 28~78 GHz mmWave communications for cellular
  - Terahertz communications
  - Free space optical communications

- Spectrum efficiency enhancement
  - Cognitive radio
  - Interference alignment and cancellation
  - Massive MIMO
  - Device-to-device communications
  - Full duplex transmissions

- Network densification
  - Small cells (HetNet)
    - Macro, micro, pico, metro, relays
  - Femtocells

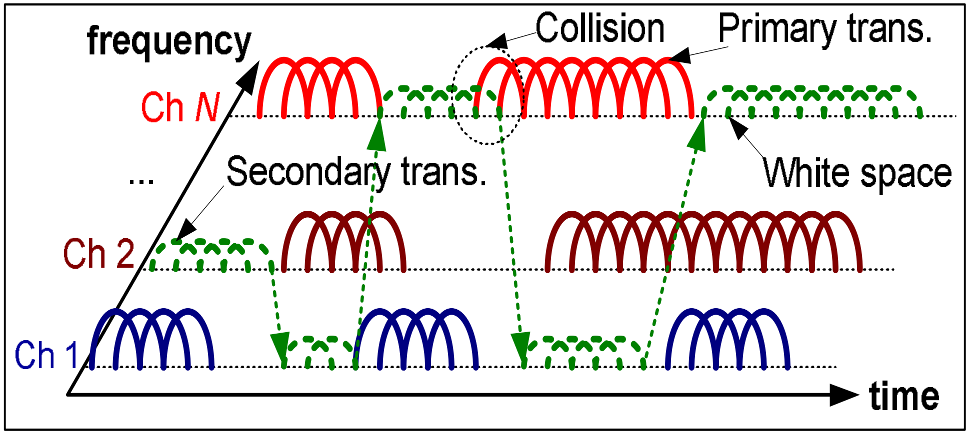
The Argos testbed developed at Rice

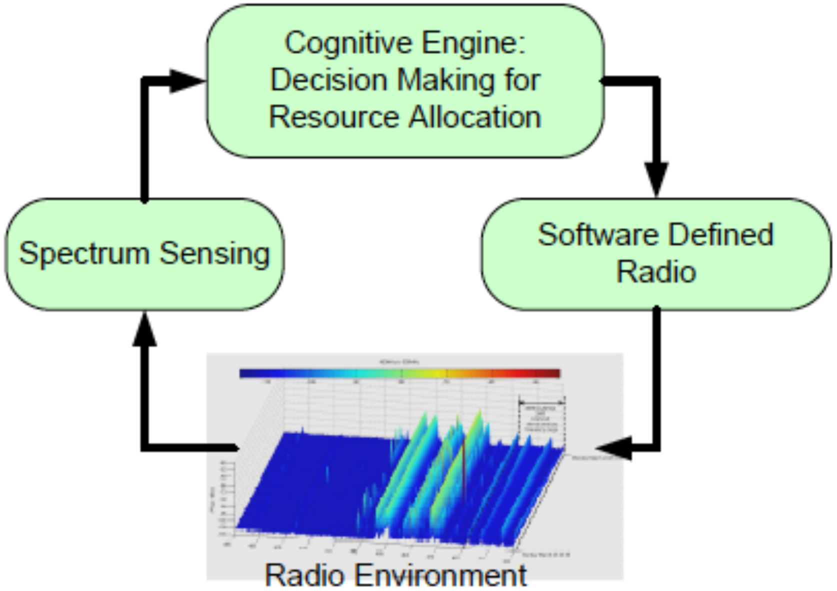
Video over CR Networks

Technical Challenges and Existing Solutions

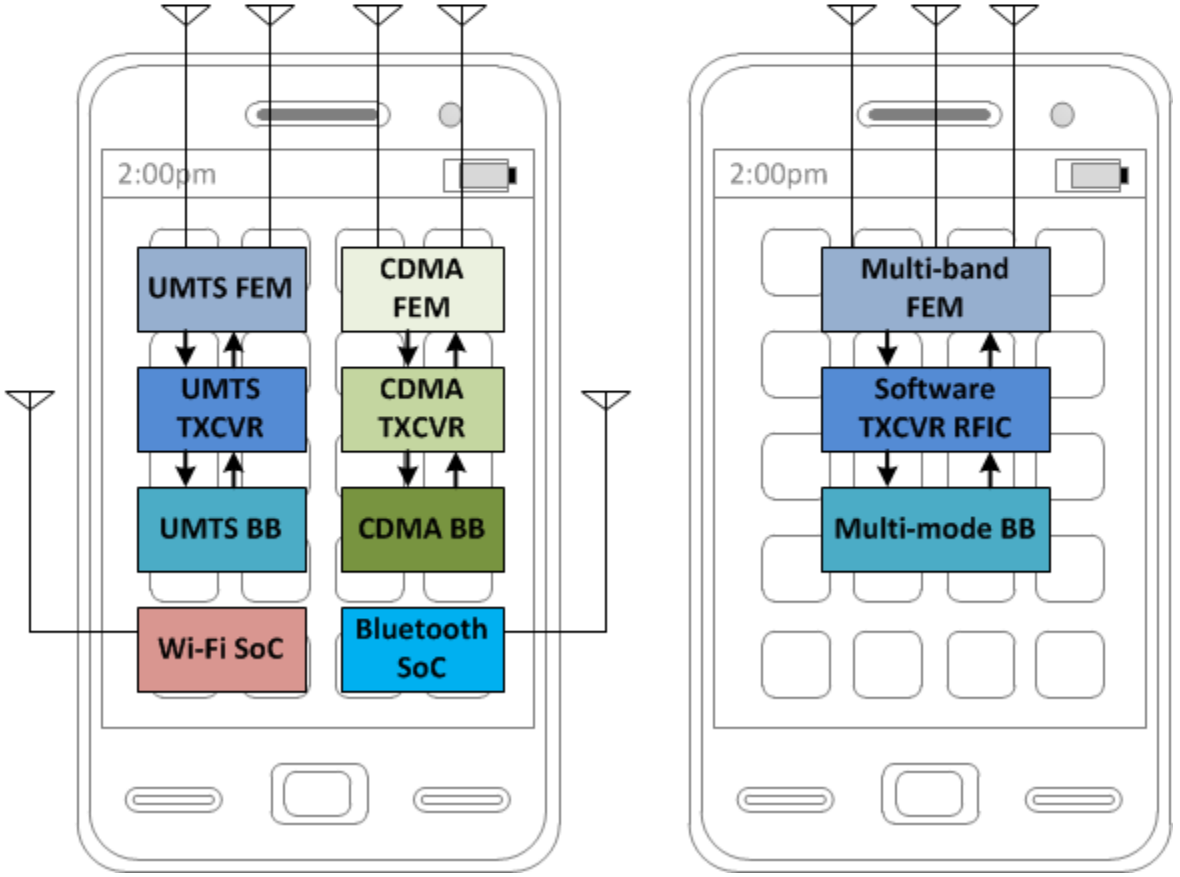
Cognitive Radio Preliminaries

- Driven by the discrepancy of spectrum deficit and low utilization of allocated spectrum found by measurement studies ➔ Share spectrum between primary and secondary users
- Enabled by the advances in software defined radio (SDR)
- Dynamic spectrum access (DSA) and the cognitive loop (how a driver behaves)
- DSA, underlay CR networks, spectrum leasing/auction, radio map database



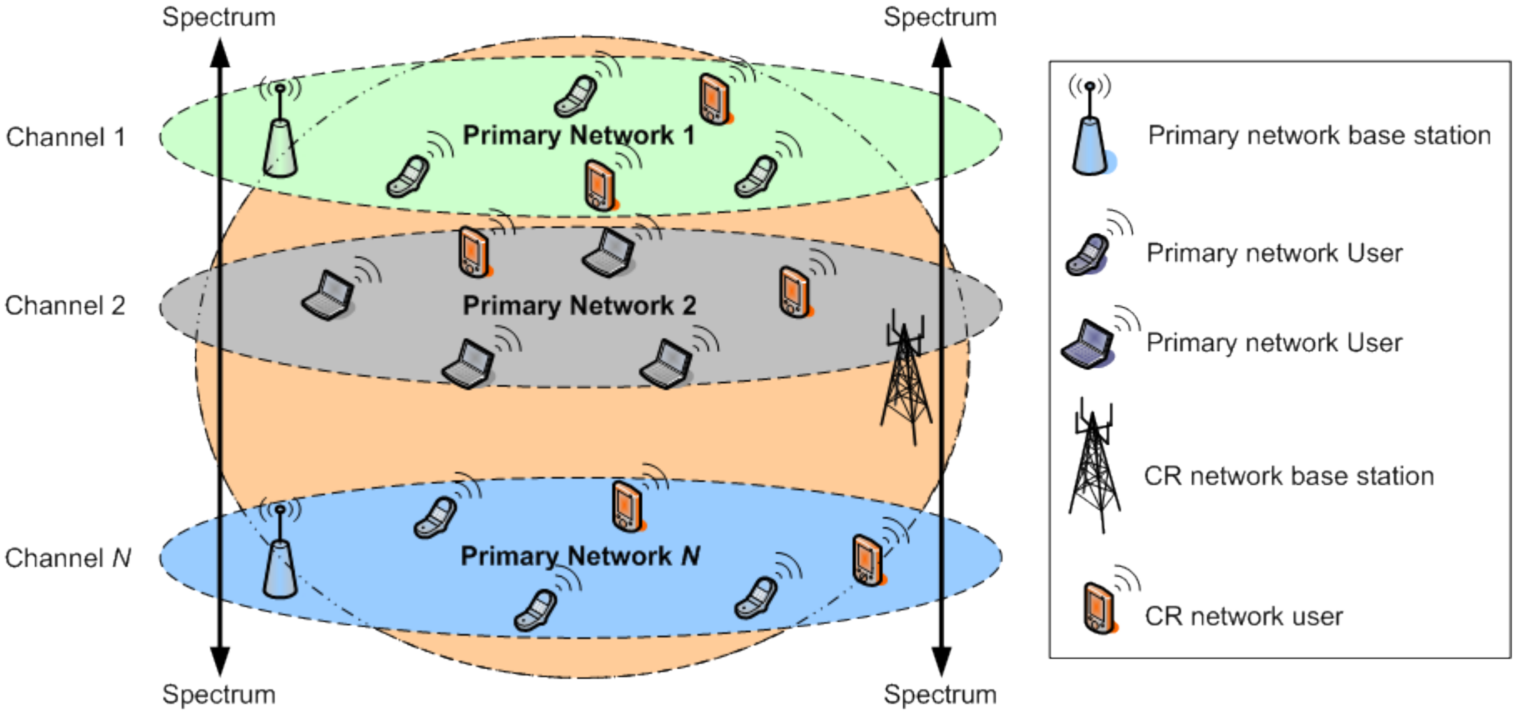


Software Defined Radio



Network Model/Challenges

Challenges: coexistence of multiple heterogeneous networks in the spectrum eco-system, lack of control and coordination (e.g., legacy systems), small timescales, additional dimension of dynamics and errors, truly cross-layer design and optimization, …



Some Existing Solutions on Video over CR Networks

- The mainstream CR research has been focused on spectrum sensing and access techniques in the past decade
- Truly cross-layer design and optimization
- Resource management: time and frequency allocation, modulation and coding scheme selection, power adaptation
  - [Soltani13, Ding13, Bocus12]: Resource allocation and routing
  - [Hu10, Luo11, Kushwaha08]: Video coding and adaptive modulation
- Buffer storage management
  - [Yao13]: Adapt the playout speed when buffer occupancy is low
  - [Li10]: Allocating channels more to CUs with low buffer storage

Some Existing Solutions on Video over CR Networks

- Interference management
    - [Guan11, Saki14]: Power adaptation
    - [Xu14]: Interference alignment
- Cross-layer optimization
    - [Yao13, Jiang12]: Impact of content-type and buffer storage
    - [Kushwaha08, Guan11, Saki14]: QoE/QoS driven cross-layer optimization
- Trade-off among multiple objectives
    - [H10, Saki14, Xu14]: Cus performance versus PUs performance
    - [Luo11]: CUs' video quality versus delay
    - [Hu10, Jiang12]: Fairness among PUs and multiple CUs

Case Study I

Scalable Video Multicast in Cellular CR Networks

Joint work with Donglin Hu, Thomas Hou and Jeffrey Reed

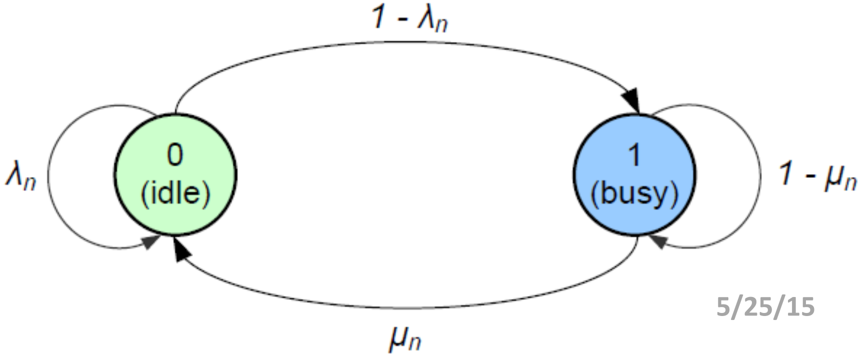
Synopsis

- Problem
  - Scalable video multicast in cognitive radio networks
- Approach
  - Fine grained scalability (FGS) video
  - Cross-layer optimization
  - Opportunistic spectrum access
- Main results
  - Greedy algorithms for reduced complexity with proven performance bound
  - Simulation validation

Network Model

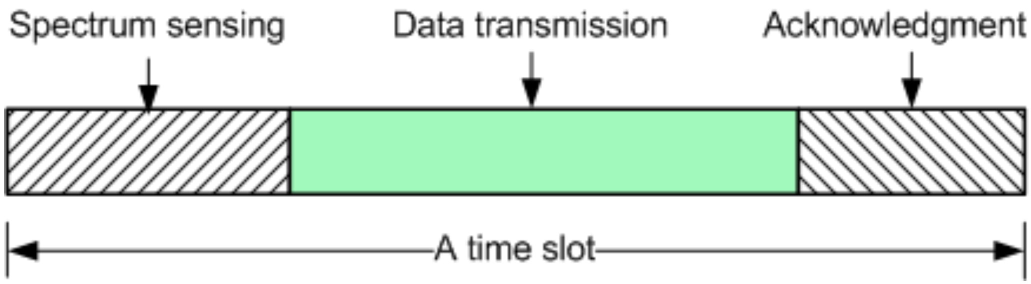
- A spectrum band with *N* channels
- Primary networks
  - Each assigned to a primary network
  - Users access the channels following a synchronous slot structure
  - Evolution of each channel
    - Independent, discrete-time Markov process
  - Network status vector

$$\vec{S}(t) = [S_1(t), S_2(t), \cdots, S_N(t)]$$



Network Model: Secondary Network

- An infrastructure-based CR network collocated with the *N* primary networks
- A base station multicasts *G* real-time videos to *G* groups of users
- Exploiting the transmission opportunities in the *N* channels
- Each time slot
  - Sense channel set $\mathcal{A}_1$ and access channel set $\mathcal{A}_2$

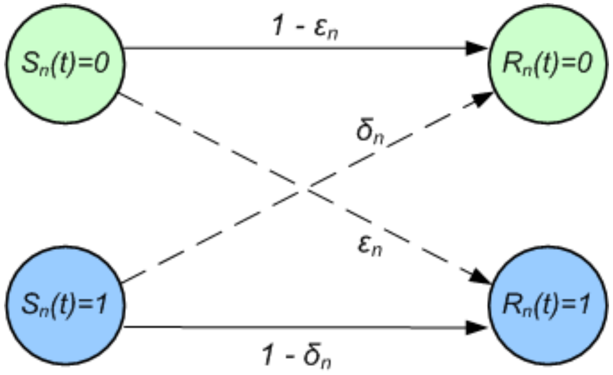


Design Considerations

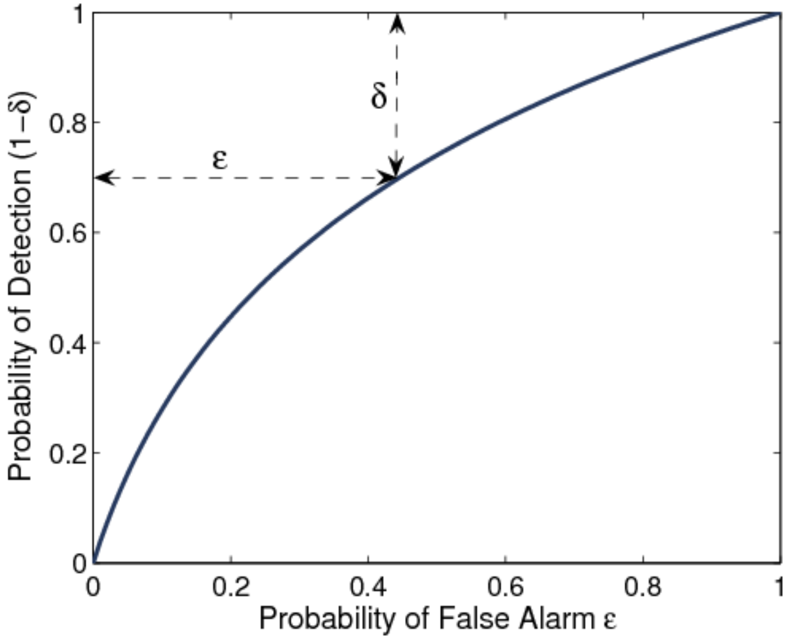
- Sensing errors
- Predict future channel states
- The tension between secondary user video quality and primary user protection
- Heterogeneous user channels
- Fairness among groups and users
- Complexity versus performance

Spectrum Sensing and Sensing Errors

- Two kinds of sensing errors
  - False alarm: waste of transmission opportunity
  - Miss detection: collision



- Characterized by the *Receiver Operation Characteristics* curve



Spectrum Sensing (contd.)

- Belief vector and sensing result in slot *t*

$$\vec{a}(t) = [a_1(t), a_2(t), \cdots, a_N(t)] \qquad \vec{R}(t) = [R_1(t), R_2(t), \cdots, R_N(t)]$$

- If channel *n* is not sensed in slot *t*

$$a_n(t) = P(S_n(t) = 0|\theta_n) = \lambda_n a_n(t-1) + \mu_n[1 - a_n(t-1)]$$

- If channel *n* is sensed in slot *t* with result 0

$$a_n(t) \;=\; P(S_n(t) = 0|R_n(t) = 0, \theta_n) = \frac{\pi_n(t)(1-\epsilon_n)}{\pi_n(t)(1-\epsilon_n) + [1-\pi_n(t)]\delta_n}$$

- If channel *n* is sensed in slot *t* with result 1

$$a_n(t) = P(S_n(t) = 0|R_n(t) = 1, \theta_n) = \frac{\pi_n(t)\epsilon_n}{\pi_n(t)\epsilon_n + [1-\pi_n(t)](1-\delta_n)}$$

- Predicting future channel availability

$$\hat{a}_n(t+\tau) = (\lambda_n - \mu_n)^\tau a_n(t) + \mu_n\left[1 - (\lambda_n - \mu_n)^\tau\right] / \left[1 - (\lambda_n - \mu_n)\right]$$

Opportunistic Channel Access

- Primary user protection
  - Maximum allowed collision probability with primary users in channel *n*, γ_n

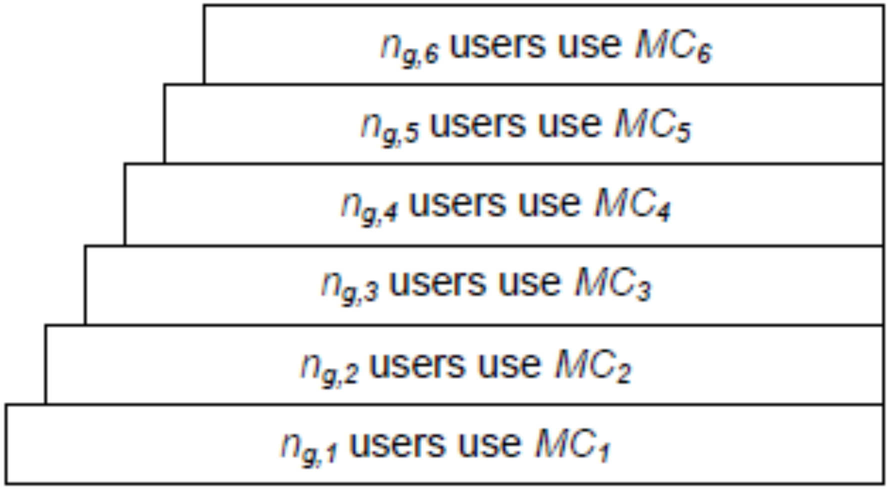
$$p_n^{tr}(t)\left[1 - a_n(t)\right] \le \gamma_n$$

- Opportunistic channel access

$$p_n^{tr}(t) = \min\left\{1, \gamma_n / [1 - a_n(t)]\right\}$$

Modulation-Coding Schemes

- *M* modulation and forward error correction schemes: MC_m, $m=1, 2, \ldots M$
  - *QPSK, 16-QAM, 64-QAM, FEC rates 1/2, 2/3, 3/4*
- Classify multicast users in group *g* according to the highest modulation that can be received



$n_{g,6}$ users use MC_6

$n_{g,5}$ users use MC_5

$n_{g,4}$ users use MC_4

$n_{g,3}$ users use MC_3

$n_{g,2}$ users use MC_2

$n_{g,1}$ users use MC_1

FGS Video and Performance Measure

- Fine Grained Scalability (FGS) video
  - One base layer (BL), one enhancement layer (EL)
  - The EL can be truncated at any bit location, while the remaining bits are still useful for decoding
- PSNR of FGS video

$$Q_g(R_g) = Q_g^b + \beta_g(R_g - R_g^b) = Q_g^b + \beta_g R_g^e$$

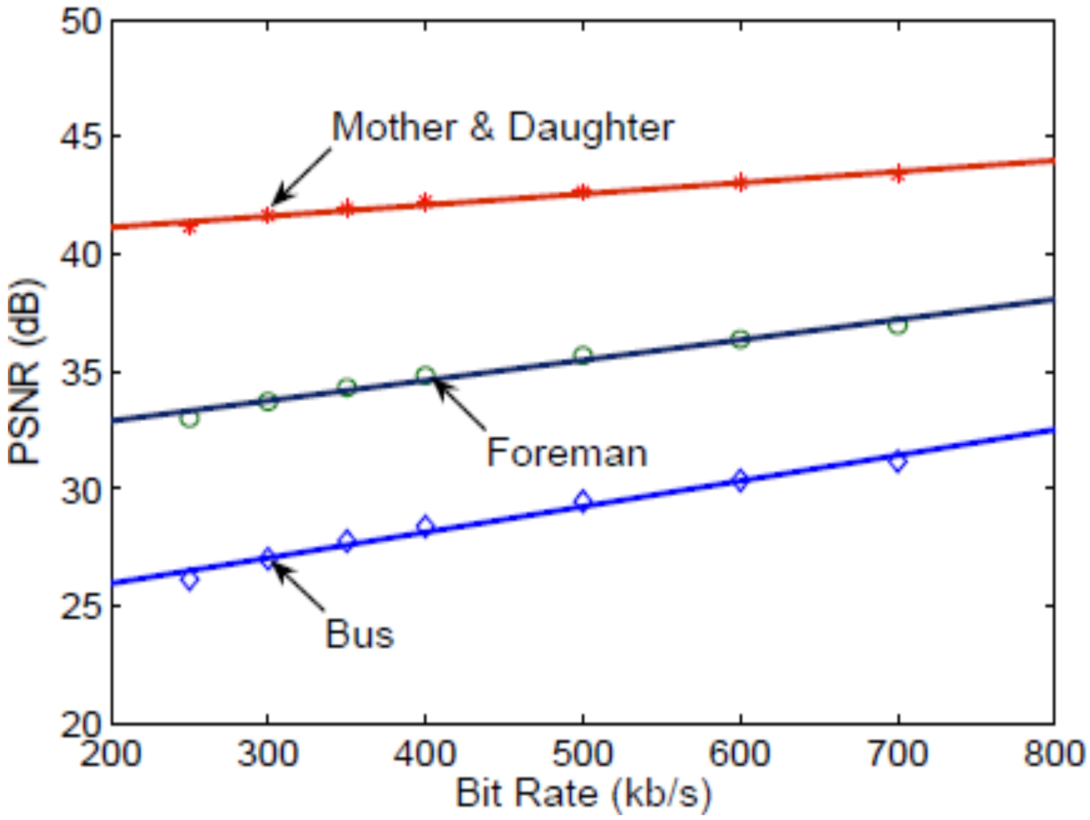
- Utility of a multicast group

$$U_g = \sum_{k=1}^{M} (n_{g,k} - n_{g,k+1}) \log \left(Q_g^b + \beta_g \sum_{m=1}^{k} R_{g,m}^e \right)$$

M. van der Schaar, S. Krishnamachari, S. Choi, and X. Xu, "Adaptive cross-layer protection strategies for robust scalable video transmission over 802.11 WLANs," *IEEE JSAC*, vol. 21, no. 10, pp. 1752–1763, Dec. 2003.

FGS Video Model Validation

- Three test sequences
  - *Bus*
  - *Foreman*
  - *Mother & Daughter*
- Common Intermediate Format (CIF 352×288)
- MPEG-4 FGS codec



Outline of the Proposed Approach

- Address heterogeneous user channels
  - FGS: base layer to all at MC1, adjust EL rate for each user group with identical channel conditions
  - Base layer is transmitted first in each GOP interval, with retransmissions if necessary
  - Enhancement sub-layers next …
- Determine the partitioning of the EL
  - *M* sub-layers, one for each of MC schemes
  - Maximizing the overall utility of all users
  - First solved for each GoP, then refined for each slot
- Schedule the tiles to channels for transmission
- Access channels opportunistically according to $p_n^{tr}(t)$

OPT-Part: The EL Partition and Tile Allocation Problem

- Executed at the beginning of a Group of Picture (GoP) window
- Non-linear integer programming problem

maximize:

$$U(\vec{l}) = \sum_{g=1}^{G}\sum_{k=1}^{M}(n_{g,k} - n_{g,k+1}) \times \log\left[Q_g^b + \beta_g \sum_{m=1}^{k} b_{g,m} l_{g,m}\right]$$

subject to:

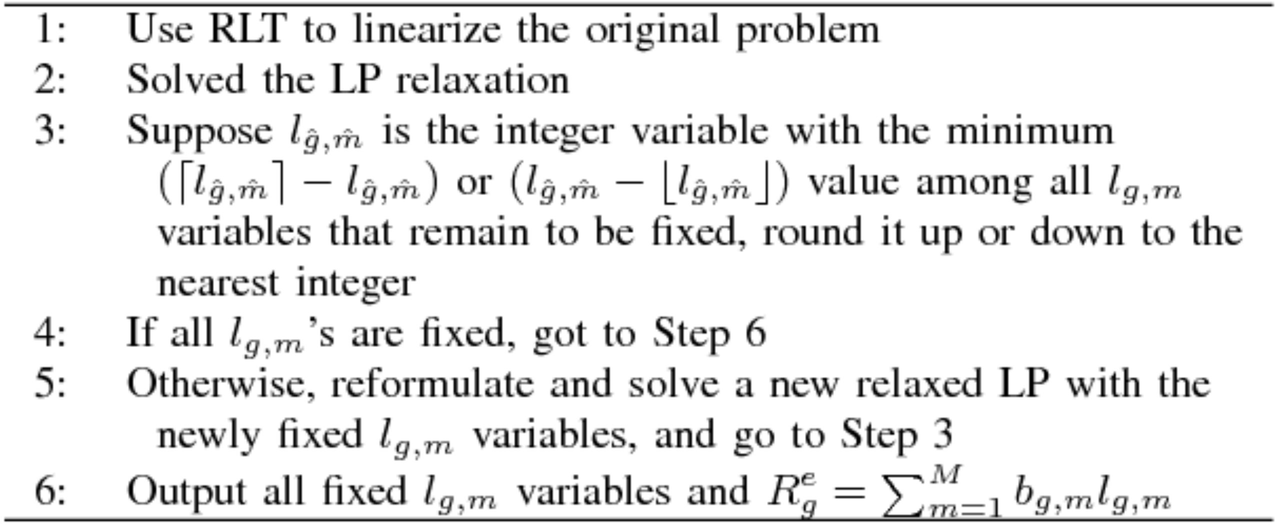
$$\sum_{g=1}^{G}\sum_{m=1}^{M} l_{g,m} \leq T_e \quad g \in [1, \cdots, G]$$

$$\sum_{m=1}^{M} b_{g,m} l_{g,m} \leq \bar{R}_g^e, \ g \in [1, \cdots, M]$$

$$l_{g,m} \geq 0, \ m \in [1, \cdots, M], g \in [1, \cdots, G].$$

The Sequential Fix (SF) Algorithm

- Use the Reformulation-Linearization Technique (RLT) to obtain an LP relaxation
- Iteratively solve the LP, fixing one integer variable at a time

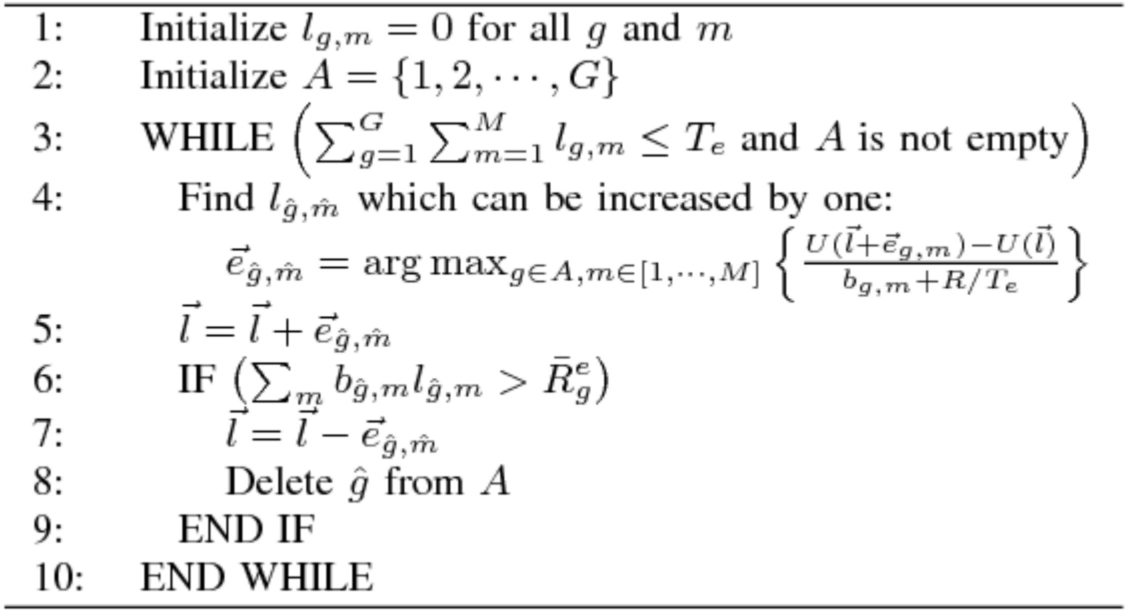


```
1: Use RLT to linearize the original problem
2: Solved the LP relaxation
3: Suppose $l_{\hat{g},\hat{m}}$ is the integer variable with the minimum
     $(\lceil l_{\hat{g},\hat{m}} \rceil - l_{\hat{g},\hat{m}})$ or $(l_{\hat{g},\hat{m}} - \lfloor l_{\hat{g},\hat{m}} \rfloor)$ value among all $l_{g,m}$
     variables that remain to be fixed, round it up or down to the
     nearest integer
4: If all $l_{g,m}$'s are fixed, got to Step 6
5: Otherwise, reformulate and solve a new relaxed LP with the
     newly fixed $l_{g,m}$ variables, and go to Step 3
6: Output all fixed $l_{g,m}$ variables and $R_g^e = \sum_{m=1}^{M} b_{g,m} l_{g,m}$
```

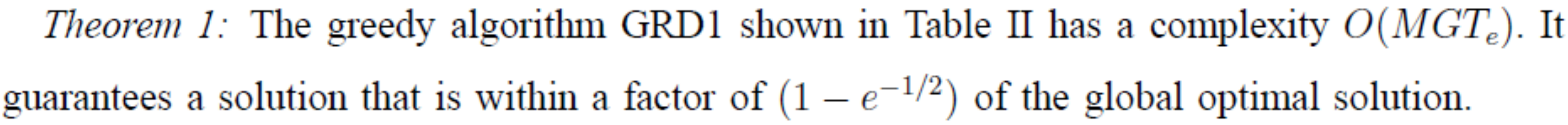
S. Kompella, S. Mao, Y. Hou, and H. Sherali, "On path selection and rate allocation for video in wireless mesh networks," *IEEE/ACM Trans. Netw.*, vol. 17, no. 1, pp. 212–224, Feb. 2009.

The Greedy Algorithm GRD1

- Exploiting the inherent priority structure of FGS video and the MC schemes



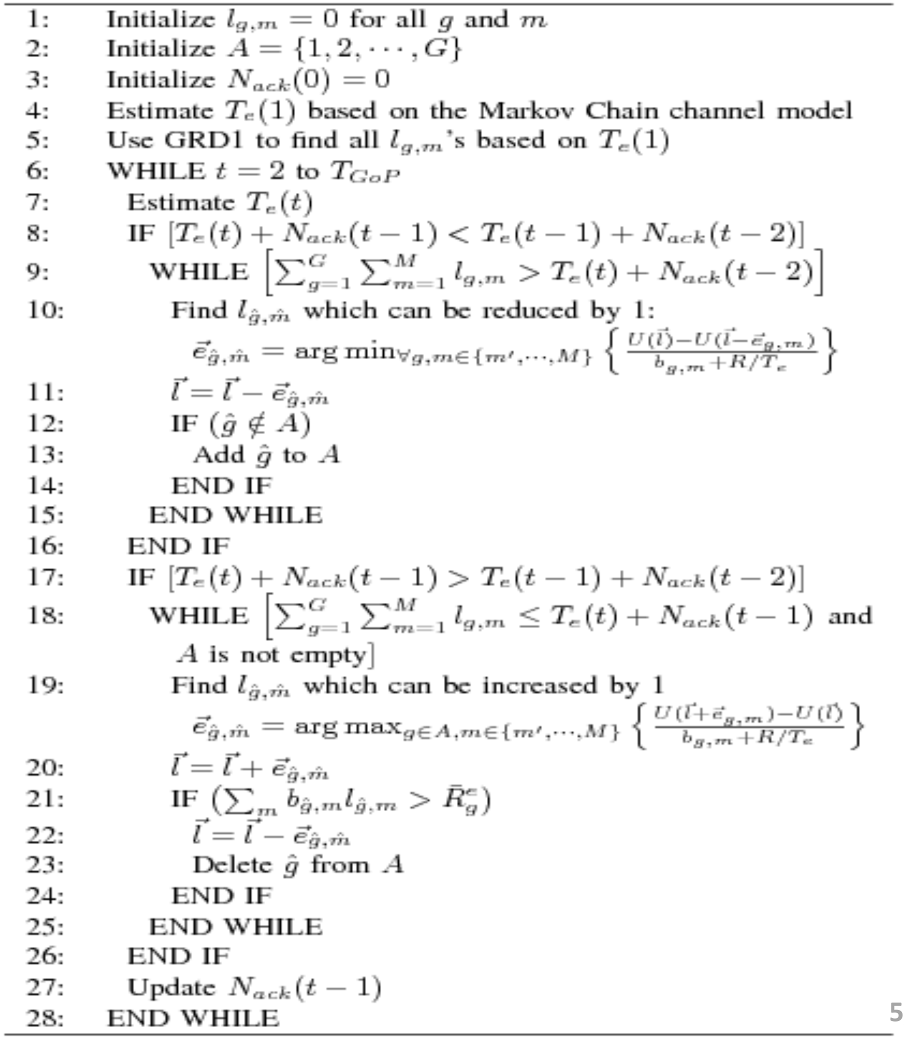
```
Initialize $l_{g,m} = 0$ for all $g$ and $m$
Initialize $A = \{1, 2, \cdots, G\}$
WHILE $\left(\sum_{g=1}^{G} \sum_{m=1}^{M} l_{g,m} \leq T_e$ and $A$ is not empty$\right)$
    Find $l_{\hat{g},\hat{m}}$ which can be increased by one:
        $\vec{e}_{\hat{g},\hat{m}} = \arg\max_{g \in A, m \in [1,\cdots,M]} \left\{ \frac{U(\vec{l}+\vec{e}_{g,m}) - U(\vec{l})}{b_{g,m} + R/T_e} \right\}$
    $\vec{l} = \vec{l} + \vec{e}_{\hat{g},\hat{m}}$
    IF $\left(\sum_m b_{\hat{g},m} l_{\hat{g},m} > \bar{R}_g^e\right)$
        $\vec{l} = \vec{l} - \vec{e}_{\hat{g},\hat{m}}$
        Delete $\hat{g}$ from $A$
    END IF
END WHILE
```



Theorem 1: The greedy algorithm GRD1 shown in Table II has a complexity $O(MGT_e)$. It guarantees a solution that is within a factor of $(1 - e^{-1/2})$ of the global optimal solution.

The Greedy Algorithm GRD2

- With recent feedback: better prediction of channel status in a sliding window of T_{est}, which is related to the channel coherence time
- Adjust the tile allocations in each time slot
- Complexity
  - O(MGK)
  - $K << T_e$



```
Initialize $l_{g,m} = 0$ for all $g$ and $m$
Initialize $A = \{1, 2, \cdots, G\}$
Initialize $N_{ack}(0) = 0$
Estimate $T_e(1)$ based on the Markov Chain channel model
Use GRD1 to find all $l_{g,m}$'s based on $T_e(1)$
WHILE $t = 2$ to $T_{GoP}$
  Estimate $T_e(t)$
  IF $[T_e(t) + N_{ack}(t-1) < T_e(t-1) + N_{ack}(t-2)]$
    WHILE $\left[\sum_{g=1}^{G} \sum_{m=1}^{M} l_{g,m} > T_e(t) + N_{ack}(t-2)\right]$
      Find $l_{\hat{g},\hat{m}}$ which can be reduced by 1:
        $\vec{e}_{\hat{g},\hat{m}} = \arg\min_{\forall g, m \in \{m', \cdots, M\}} \left\{ \frac{U(\vec{l}) - U(\vec{l} - \vec{e}_{g,m})}{b_{g,m} + R/T_e} \right\}$
      $\vec{l} = \vec{l} - \vec{e}_{\hat{g},\hat{m}}$
      IF $(\hat{g} \notin A)$
        Add $\hat{g}$ to $A$
      END IF
    END WHILE
  END IF
  IF $[T_e(t) + N_{ack}(t-1) > T_e(t-1) + N_{ack}(t-2)]$
    WHILE $\left[\sum_{g=1}^{G} \sum_{m=1}^{M} l_{g,m} \leq T_e(t) + N_{ack}(t-1)\right.$ and
      $A$ is not empty$]$
      Find $l_{\hat{g},\hat{m}}$ which can be increased by 1
        $\vec{e}_{\hat{g},\hat{m}} = \arg\max_{g \in A, m \in \{m', \cdots, M\}} \left\{ \frac{U(\vec{l} + \vec{e}_{g,m}) - U(\vec{l})}{b_{g,m} + R/T_e} \right\}$
      $\vec{l} = \vec{l} + \vec{e}_{\hat{g},\hat{m}}$
      IF $(\sum_{m} b_{\hat{g},m} l_{\hat{g},m} > \bar{R}_g^e)$
        $\vec{l} = \vec{l} - \vec{e}_{\hat{g},\hat{m}}$
        Delete $\hat{g}$ from $A$
      END IF
    END WHILE
  END IF
  Update $N_{ack}(t-1)$
END WHILE
```

The Tile Scheduling Algorithm

- In each slot: which tile to transmit, over which channel?
- Reward: Increase in the total utility if one extra tile is successfully decoded

$$\mathrm{Inc}(g,m,i) = \sum_{k=m}^{M}(n_{g,k} - n_{g,k+1}) \times \log\left[1 + \frac{\beta_g b_{g,m}}{Q_g^b + \beta_g \sum_{u=1}^{m-1} b_{g,u} l_{g,u} + (i-1)\beta_g b_{g,m}}\right]$$

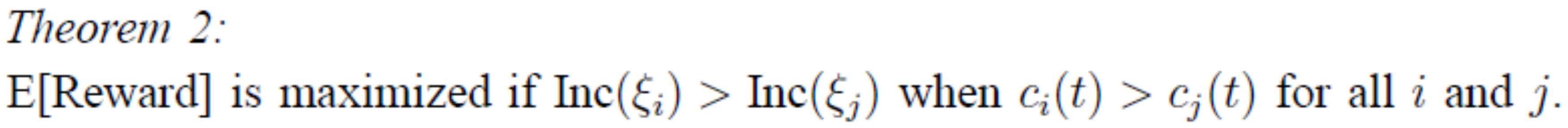
- The success probability on channel *n*

$$c_n(t) = p_n^{tr}(t) a_n(t)$$

- The tile scheduling problem

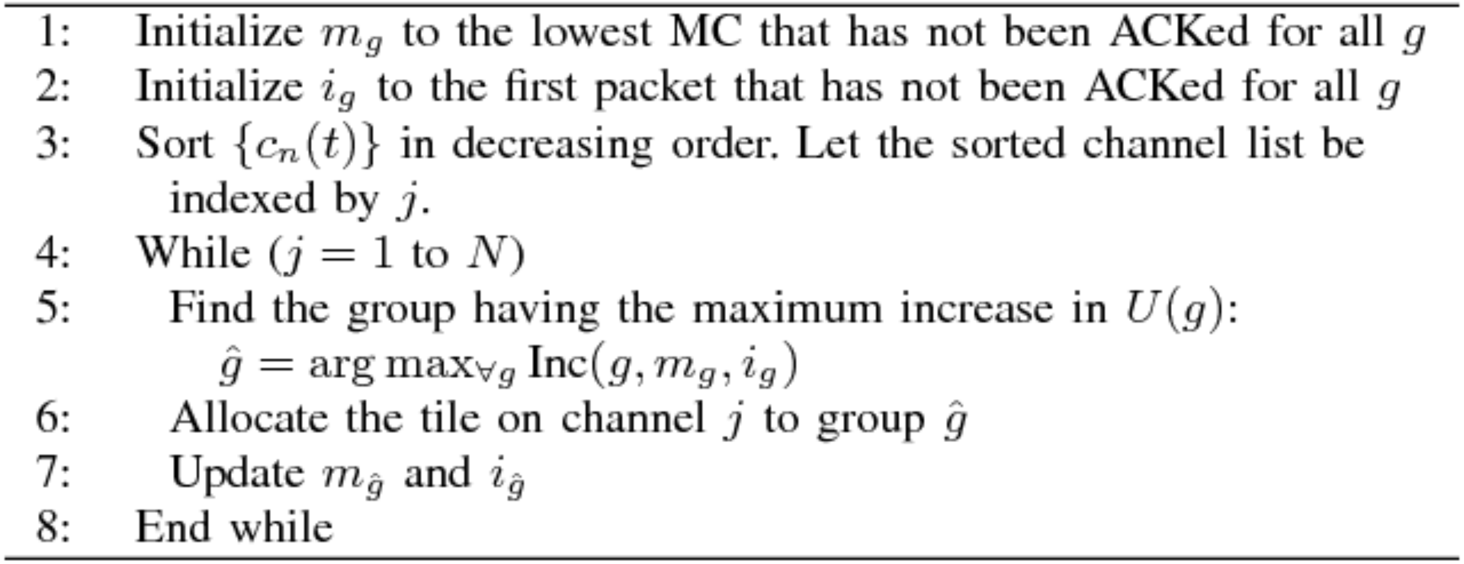
$$\text{maximize:} \quad \mathrm{E}[\mathrm{Reward}(\vec{\xi})] = \sum_{n=1}^{N} c_n(t) \cdot \mathrm{Inc}(\xi_n)$$

The Tile Scheduling Algorithm



Theorem 2:

E[Reward] is maximized if $\mathrm{Inc}(\xi_i) > \mathrm{Inc}(\xi_j)$ when $c_i(t) > c_j(t)$ for all i and j.



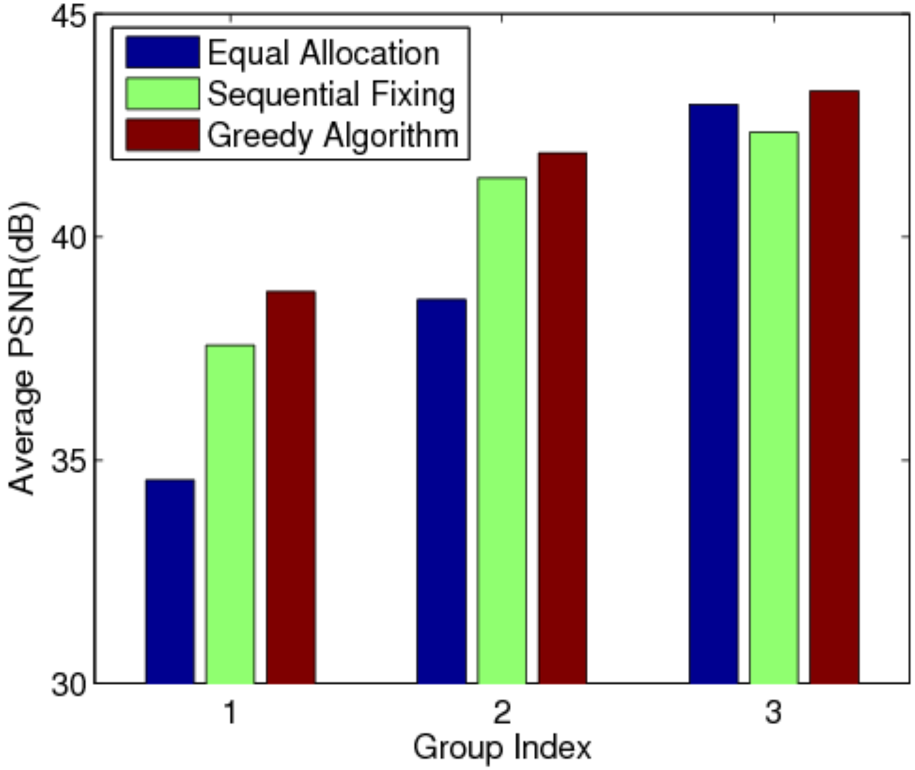
```
Initialize $m_g$ to the lowest MC that has not been ACKed for all $g$
Initialize $i_g$ to the first packet that has not been ACKed for all $g$
Sort $\{c_n(t)\}$ in decreasing order. Let the sorted channel list be
  indexed by $j$.
While ($j = 1$ to $N$)
  Find the group having the maximum increase in $U(g)$:
    $\hat{g} = \arg\max_{\forall g} \mathrm{Inc}(g, m_g, i_g)$
  Allocate the tile on channel $j$ to group $\hat{g}$
  Update $m_{\hat{g}}$ and $i_{\hat{g}}$
End while
```

- The computational complexity is O(*N*log*N*)

Simulation Settings

- Comparison of three schemes
  - Equal allocation
  - Sequential fixing
  - Greedy algorithms
- Three CIF (352×288) test sequences
  - *Bus*, *Foreman*, *Mother & Daughter*
- N=12 channels
- μ_n and λ_n chosen from (0,1), γ_n=0.2
- Average of 10 runs with 95% confidence interval

Average PSNR



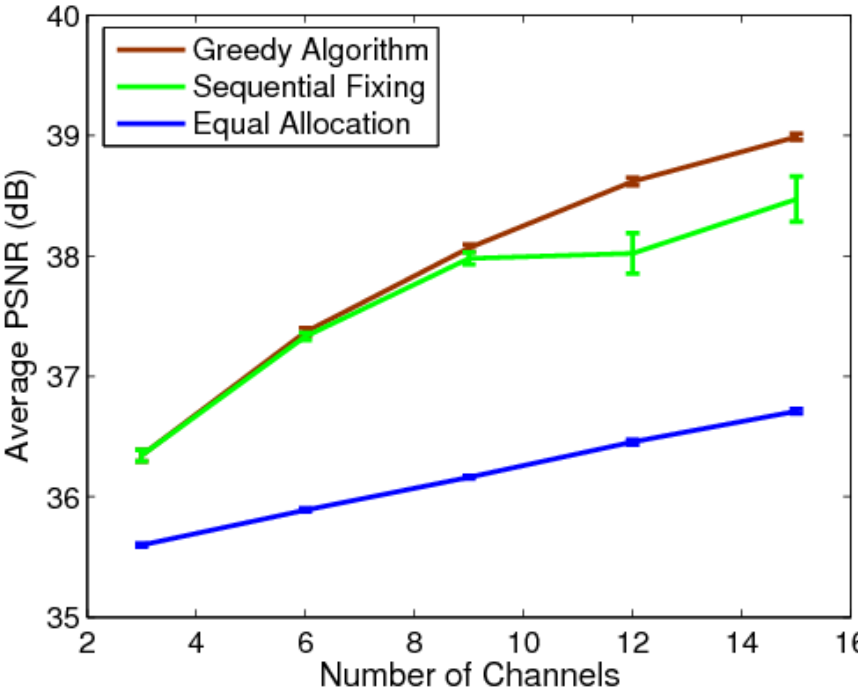
Greedy Algorithm achieves

✧ 4.2 dB over Equal Allocation

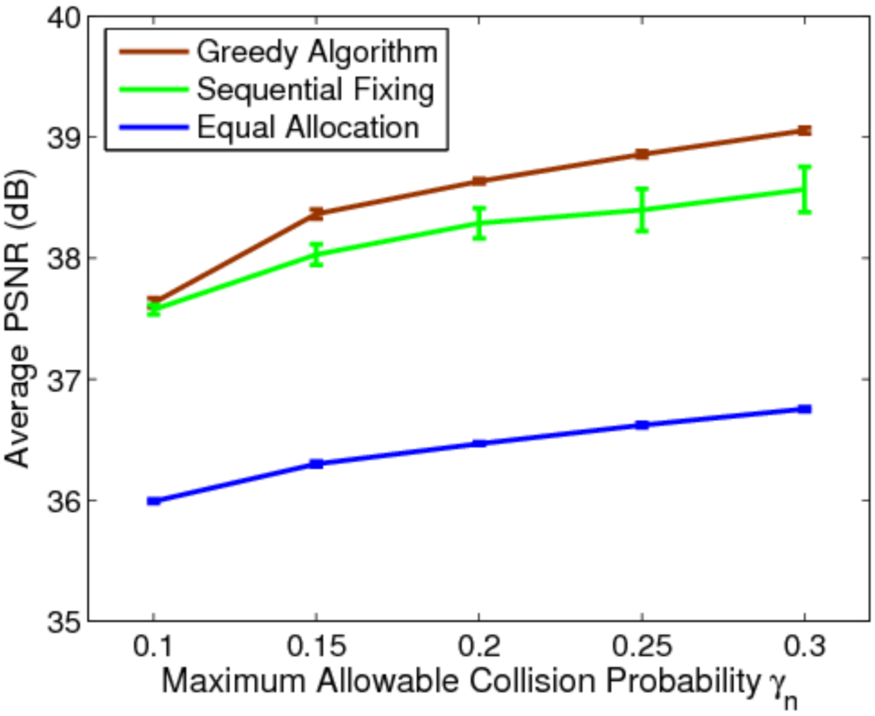
✧ 0.6 dB over Sequential Fixing

Impact of *N* and γ_n

More channels are available

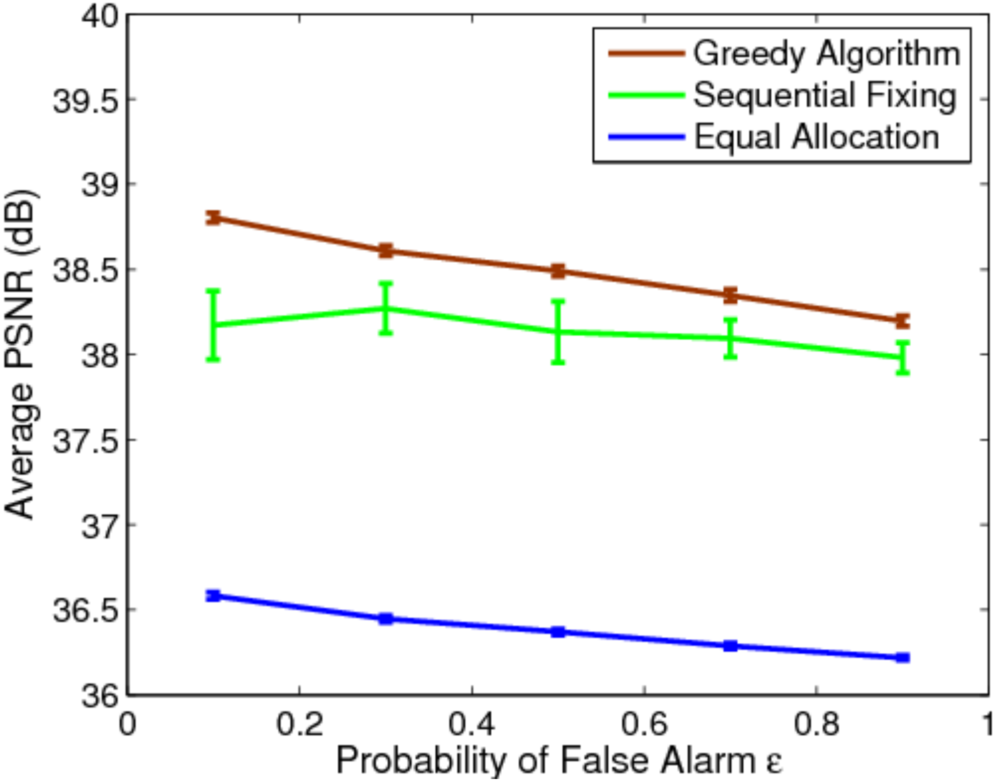


More aggressive transmissions



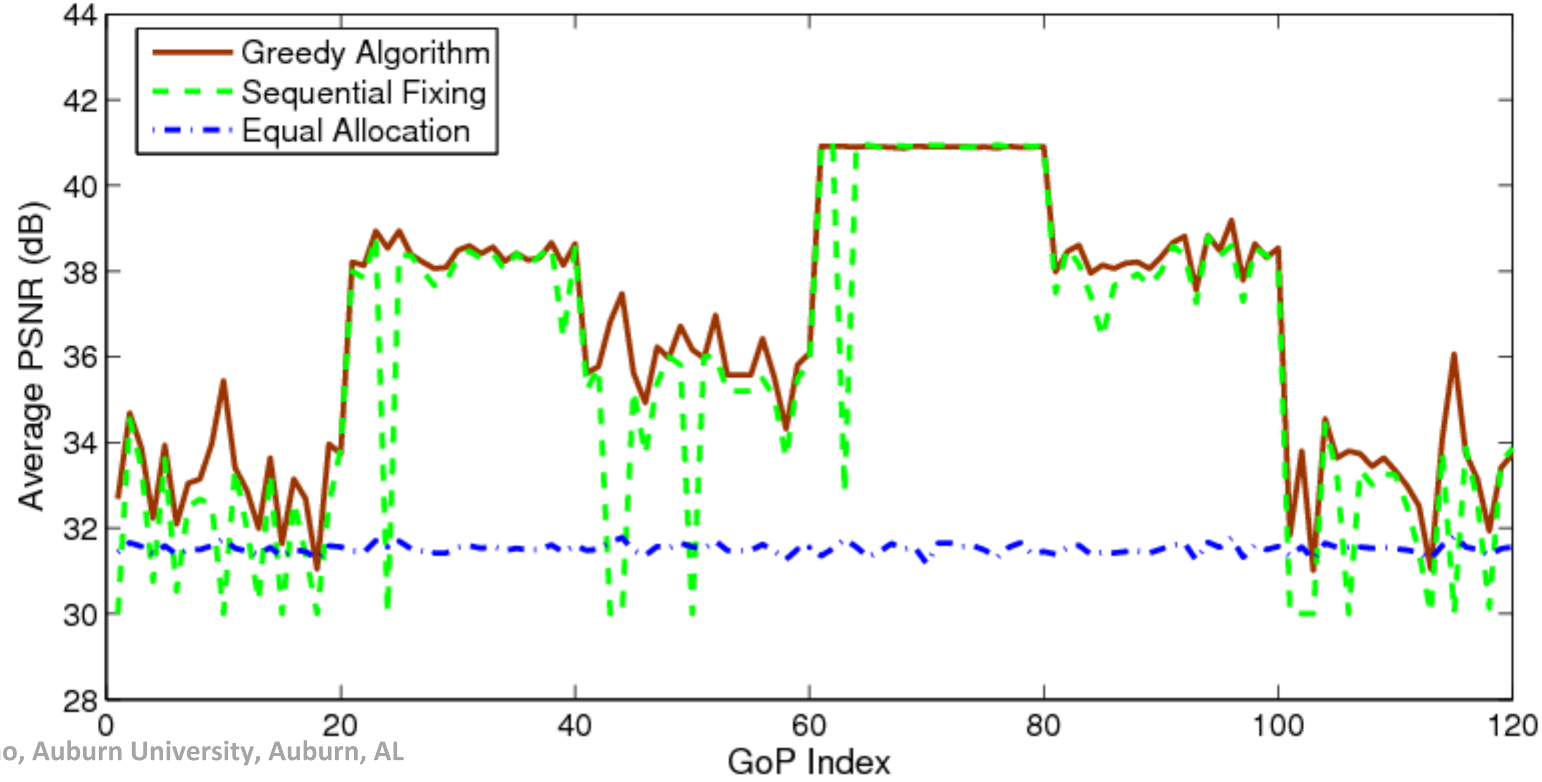
Impact of Sensing Errors

- Tested five combinations of sensing errors
  - {0.10, 0.38}, {0.30, 0.25}, {0.5, 0.17}, {0.70, 0.10}, {0.9, 0.04}
- Decrease due to waste of spectrum opportunities
- But not very sensitive to ε



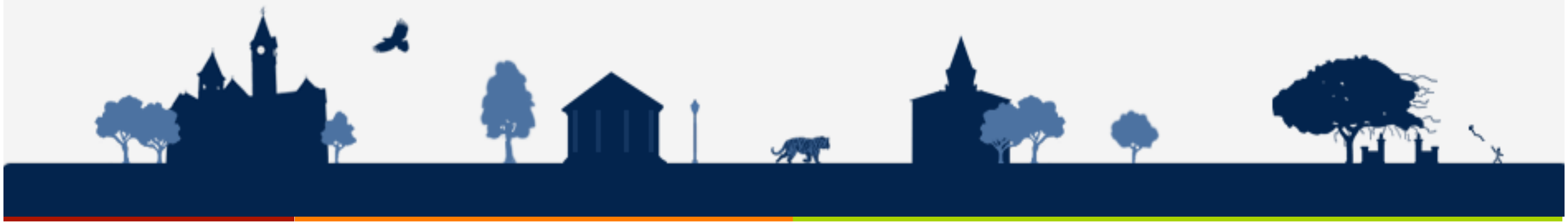
User Channel Variation

- A tagged user in Group 1
- Channel condition changes every 20 GoPs



Conclusions

- Video multicast in an infrastructure-based CR network
- Our approach
  - FGS to address heterogeneous user channels
  - Cross-layer optimization
  - Opportunistic spectrum access
  - Greedy algorithms for reduced complexity with a proven approximation ratio
- Demonstrate the viability of video over CR networks



Case Study II

Multi-user Video Streaming over Multi-hop CR Networks

Joint work with Donglin Hu

Synopsis

- Problem
  - Multi-user video streaming in ad hoc CR networks
- Approach
  - Fine grained scalability (FGS) video
  - Cross-layer optimization: an MINLP problem
  - Amplify-and-forward based “cut-through switching”
- Main results
  - Centralized sequential-fixing algorithm for lower and upper bounds
  - Dual decomposition for distributed algorithms with proven optimality
  - Simulation validation

Ad Hoc CR Network Model

- An ad hoc CR network collocated with *M* primary networks (*M* licensed channels)
- Cooperative spectrum sensing
- Multiple FGS unicast sessions

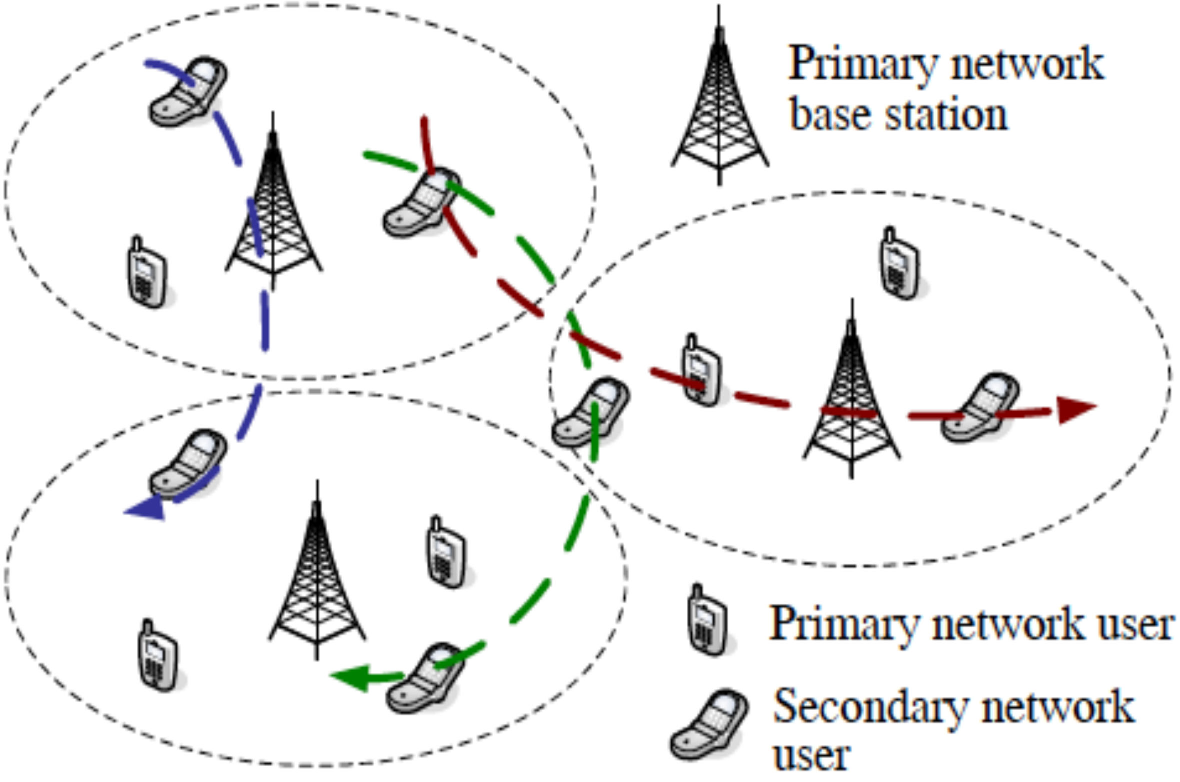


Fig. 1. Illustration of the multi-hop video CR network architecture.

“Cut-through Switching”

- Each relay has two transceivers: each receive and transmit on two orthogonal channels
- Amplify-and-forward
- To establish a “virtual” tunnel: minimum delay and jitter

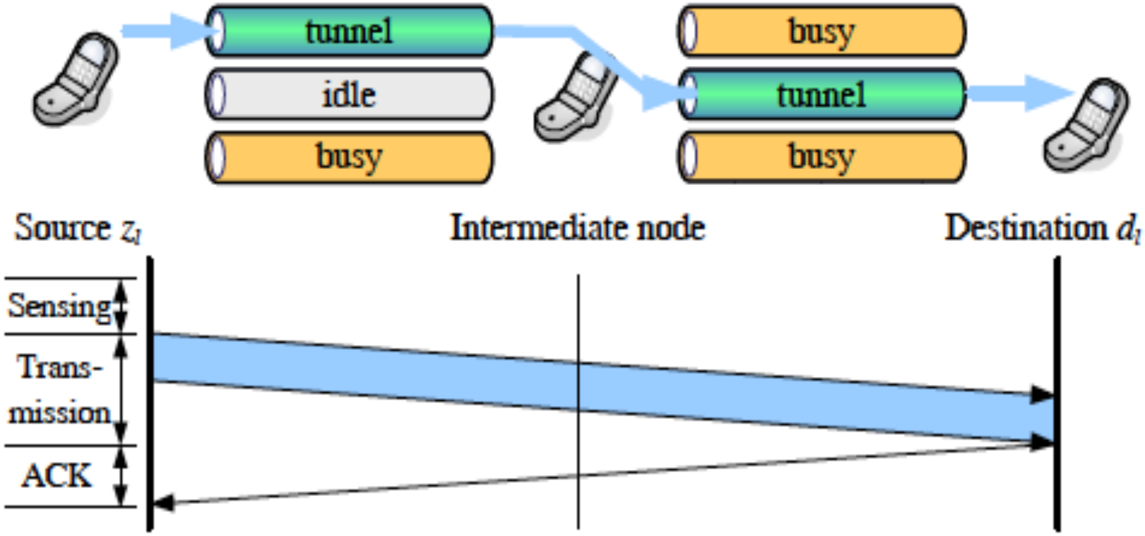


Fig. 2. The cut-through switching model for video data.

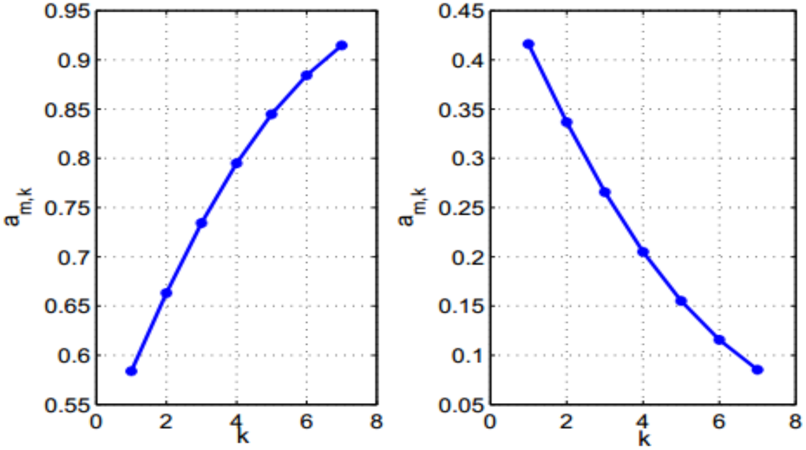
R. Ramanathan, “Challenges: a radically new architecture for next generation mobile ad-hoc networks," in *Proc. ACM MobiCom’05*, Cologne, Germany, Sept. 2005, pp. 132-139.

Cooperative Spectrum Sensing

- When *L* sensing results are available for a channel *m*

$$P_m^A(\Theta_1^m) = \left[1 + \frac{\eta_m}{1-\eta_m} \times \frac{(\delta_1^m)^{1-\Theta_1^m}(1-\delta_1^m)^{\Theta_1^m}}{(\epsilon_1^m)^{\Theta_1^m}(1-\epsilon_1^m)^{1-\Theta_1^m}}\right]^{-1}$$

$$P_m^A(\Theta_1^m, \Theta_2^m, \cdots, \Theta_l^m) = \left\{1 + \left[\frac{1}{P_m^A(\Theta_1^m, \Theta_2^m, \cdots, \Theta_{l-1}^m)} - 1\right] \times \frac{(\delta_l^m)^{1-\Theta_l^m}(1-\delta_l^m)^{\Theta_l^m}}{(\epsilon_l^m)^{\Theta_l^m}(1-\epsilon_l^m)^{1-\Theta_l^m}}\right\}^{-1}, \; l = 2, \cdots, L.$$



(a) Channel m is idle (b) Channel m is busy

Figure 4. Illustration of $a_{m,k}$ as a monotone function of k, when $\epsilon_m = 0.3$, $\delta_m = 0.3$, and $\bar{K} = 7$.

Problem Formulation

- Objective function

$$\text{maximize: } \sum_l U_l(R_l) = \sum_l \log(Q_l(R_l)).$$

$$\Downarrow$$

$$\sum_l \log(Q_l(\mathbf{E}[R_l(N_G)])) - \log(Q_l(\mathbf{E}[R_l(0)]))$$
$$= \sum_t \sum_l \{\log(Q_l(\mathbf{E}[R_l(t)])) - \log(Q_l(\mathbf{E}[R_l(t-1)]))\}$$

$$\Downarrow$$

$$= \sum_l \sum_{h \in \mathcal{P}_l} y_l^h \log\left(1 + \rho_l^t \sum_r \sum_m x_{z_l, z_l', m}^{l,h,r} (1 - p_{l,h}^r)\right)$$

$$\Downarrow$$

$$\text{max: } \sum_l \sum_{h \in \mathcal{P}_l} y_l^h \log\left(1 + \rho_l^t \sum_r \sum_m x_{z_l, z_l', m}^{l,h,r} (1 - p_{l,h}^r)\right)$$

Subject to: hardware constraint, flow conservation constraints, etc.

Centralized Scheme and Bounds

- Channel scheduling and path selection index variables

$$x_{i,j,m}^{l,h,r} = \begin{cases} 1, & \text{at link } \{i,j\}\text{, if channel } m \text{ is} \\ & \text{assigned to tunnel } r \text{ in path } \mathcal{P}_l^h \\ 0, & \text{otherwise.} \end{cases}$$

$$y_l^h = \begin{cases} 1, & \text{if video session } l \text{ selects path } \mathcal{P}_l^h \in \mathcal{P}_l \\ 0, & \text{otherwise,} \end{cases}$$

- Relaxing the binary variables to obtain and NLP
  - Solved with a constraint NLP solver
  - An upper bound
- Sequential fixing to fix the fractional variables
  - A feasible solution and a lower bound

Decomposition

- Channel scheduling problem
  - Solved with a greedy algorithm: always choose the channel with the lowest loss probability when setting up the tunnels

$$H_l^h = \max_{\mathbf{x}} \sum\nolimits_r \sum\nolimits_m x^{l,h,r}_{z_l,z'_l,m}(1-p^r_{l,h})$$

$$\text{subject to: } (19) \sim (24),\ x^{l,h,r}_{z_l,z'_l,m} \in \{0,1\},\ \text{for all } l,h,r,m.$$

- Path selection problem
  - Relaxed and solved with Dual Decomposition

$$\begin{aligned} \text{maximize:} \quad & f(\mathrm{y}) = \sum\nolimits_l \sum\nolimits_h F_l^h y_l^h \\ \text{subject to:} \quad & \sum\nolimits_l \sum\nolimits_{h \in \mathcal{P}_l} w^g_{l,h} y_l^h \leq 1,\ \text{for all } \ g \\ & y_l^h \in \{0,1\},\ \text{for all } \ l,h. \end{aligned}$$

Performance of the Algorithms

- Greedy algorithm for channel scheduling is optimal
- The optimal solution to the relaxed problems is also feasible and optimal to the original path selection problem
- The iterative algorithm is guaranteed to converge to the optimal solution

Simulation Validation

- 3 Primary networks, 10 channels, 3 video sessions

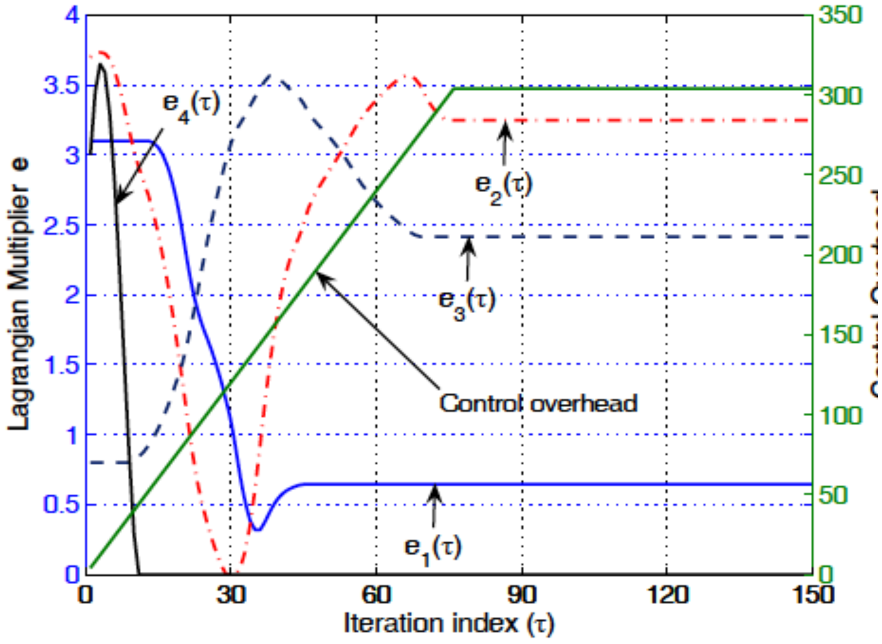


Fig. 4. Illustrate the convergence of the distributed algorithm.

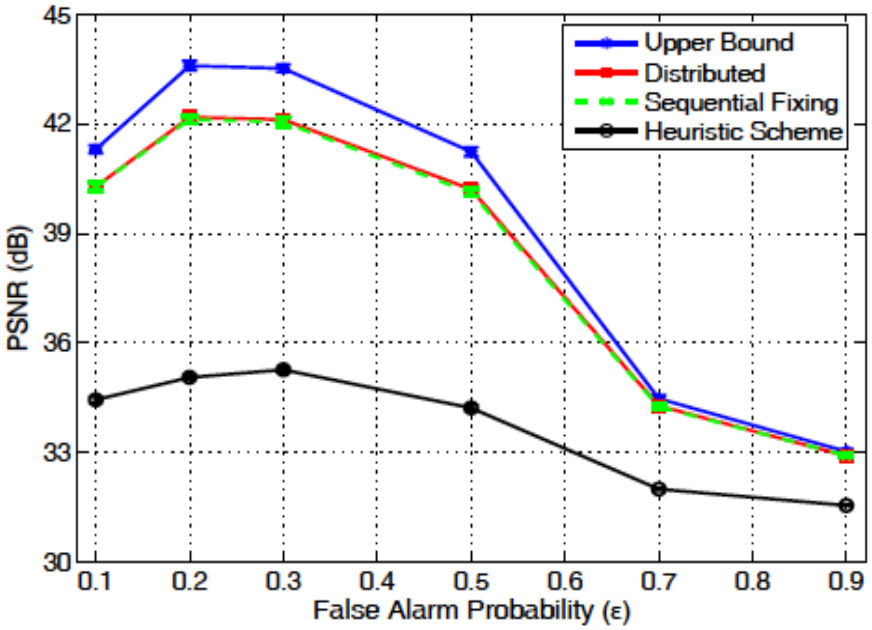


Fig. 5. Video PSNR versus spectrum sensing error.

Conclusions

- Multi-user video streaming over an ad hoc CR network
  - FGS to address heterogeneous user channels
  - Cut-through switching
- Our approach
  - Cross-layer optimization
    - Cooperative spectrum sensing, channel allocation, path selection, video quality maximization
  - Decomposition of the problem in time and into channel scheduling and path selections problems
  - Developed optimal solution algorithms

Case Study III

A Decomposition Approach to Quality-driven Multi-user Video Streaming in Cellular CR Networks

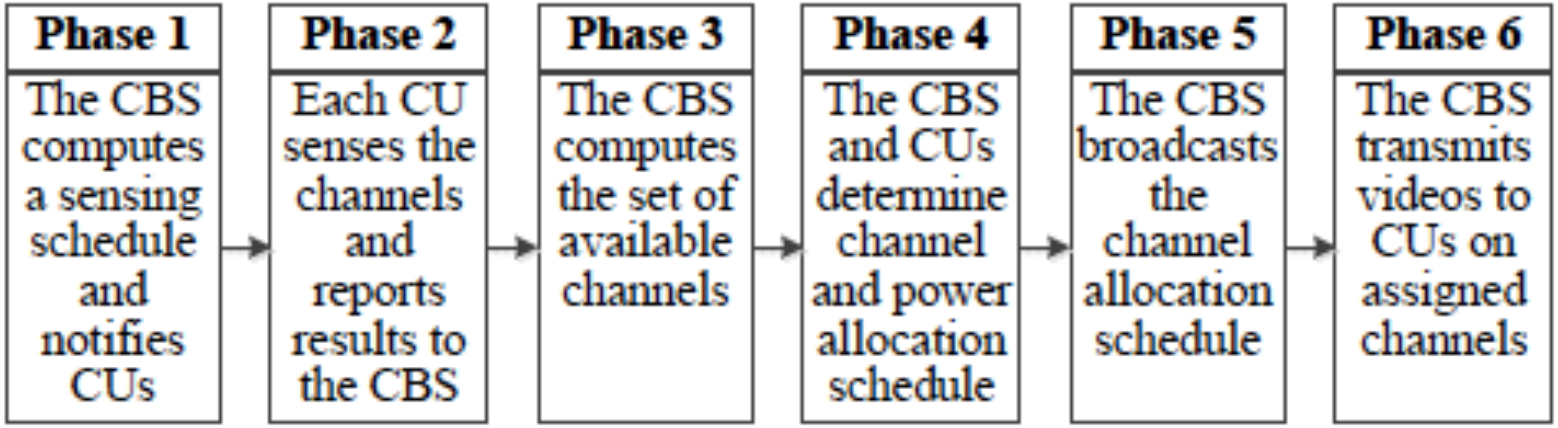
Joint work with Zhifeng He and Sastry Kompella

Synopsis

- Problem
  - Multi-user video streaming in the downlink of a cellular CR network
- Approach
  - Fine grained scalability (FGS) video
  - A holistic formulation considering
    - Energy detection based cooperative sensing, assigning CUs to channels, channel allocation and power control
- Main results
  - A decomposition approach to decouple the optimal sensing problem and the channel allocation and power control problem
  - Solution algorithms: column generation based iterative scheme
  - Without sacrificing optimality

System Model

- A primary network, N_1 licensed channels; a cognitive BS (CBS) and M CUs
- Two-state Markov channels, M video sessions, H.264 SVC (quality scalability) videos
- K power levels for CBS, channel bonding and aggregation



Phase 1 The CBS computes a sensing schedule and notifies CUs → **Phase 2** Each CU senses the channels and reports results to the CBS → **Phase 3** The CBS computes the set of available channels → **Phase 4** The CBS and CUs determine channel and power allocation schedule → **Phase 5** The CBS broadcasts the channel allocation schedule → **Phase 6** The CBS transmits videos to CUs on assigned channels

Fig. 1. Operations of CBS and CUs in a time slot.

Problem Formulation

- Channel sensing variables x_{ij}: CU *i* is assigned to sense channel *j*
- Channel assignment an power allocation variables: $0 \le y_{ijk}^h \le 1$ is the amount of time that CBS transmits to C *i* with power level *k* on channel *j* when the channel is in *h*-th state

$$\underline{\mathbf{P0}} : \max : \sum_{h=0}^{2^{N_1}-1} \sum_{i=1}^{M} \sum_{j \in \Phi_h} \sum_{k=1}^{K} w_{ijk} \cdot y_{ijk}^h \cdot P(\vec{\mathbf{S}} = \vec{\mathbf{S}}_h)$$

$$\text{s.t.} \sum_{j \in \Phi_h} \sum_{k=1}^{K} y_{ijk}^h \le C_i, \forall\, i, h$$

$$\sum_{i=1}^{M} \sum_{k=1}^{K} y_{ijk}^h \le 1, \forall\, j$$

$$\sum_{i=1}^{M} \sum_{j \in \Phi_h} \sum_{k=1}^{K} y_{ijk}^h \cdot G_k \le G_{total}, \forall\, h$$

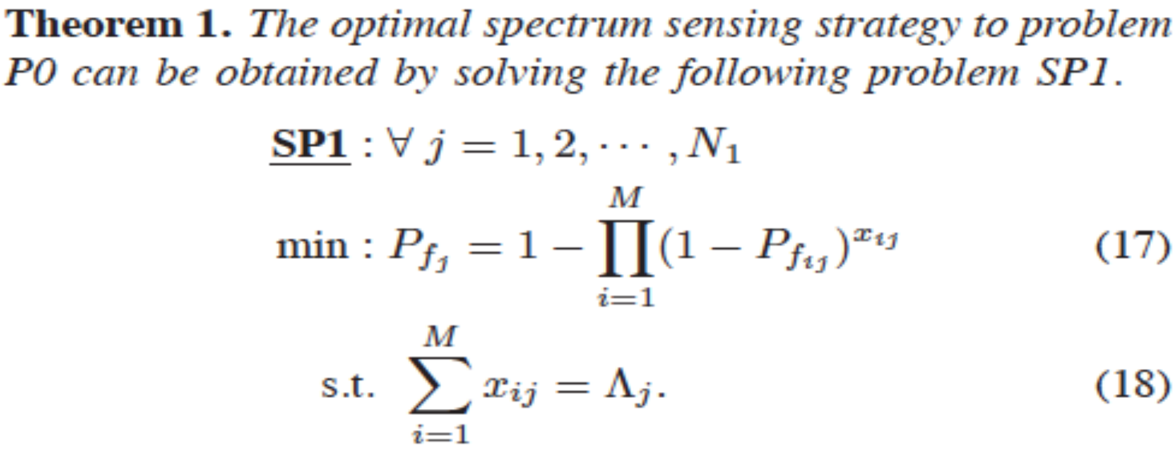
$$\sum_{i=1}^{M} x_{ij} = \Lambda_j, \forall\, j$$

$$x_{ij} = \{0, 1\}, \forall\, i, j$$

$$y_{ijk}^h \begin{cases} \in [0, 1], & \text{if } G_k d_{ij}/(n_0 B_j) \ge \bar{\gamma} \\ = 0, & \text{otherwise,} \end{cases} \quad \forall\, i, j, k.$$

Main Results

- The objective value of P0 is decreasing function of false alarm probability

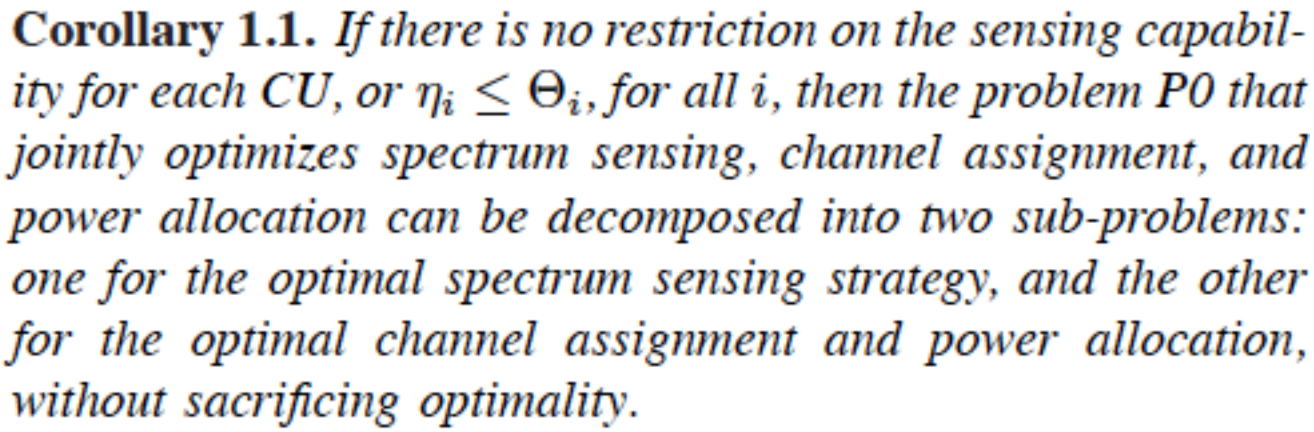


Theorem 1. *The optimal spectrum sensing strategy to problem P0 can be obtained by solving the following problem SP1.*

$$\underline{\textbf{SP1}}: \forall\, j = 1, 2, \cdots, N_1$$

$$\min : P_{f_j} = 1 - \prod_{i=1}^{M} (1 - P_{f_{ij}})^{x_{ij}} \quad (17)$$

$$\text{s.t.} \ \sum_{i=1}^{M} x_{ij} = \Lambda_j. \quad (18)$$



Corollary 1.1. *If there is no restriction on the sensing capability for each CU, or $\eta_i \leq \Theta_i$, for all i, then the problem P0 that jointly optimizes spectrum sensing, channel assignment, and power allocation can be decomposed into two sub-problems: one for the optimal spectrum sensing strategy, and the other for the optimal channel assignment and power allocation, without sacrificing optimality.*

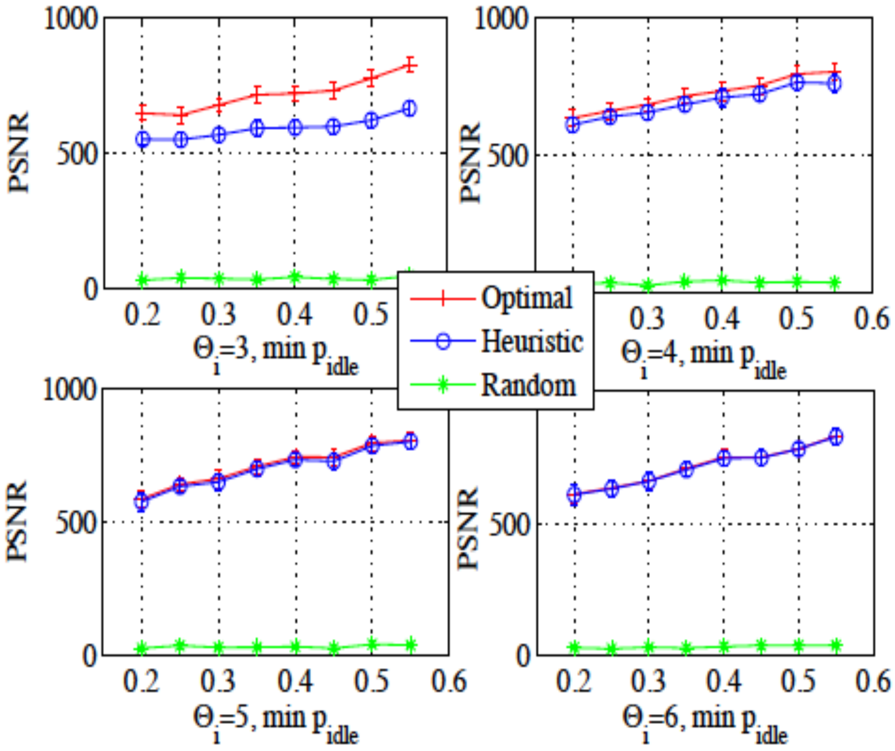
Main Results (cont'd)

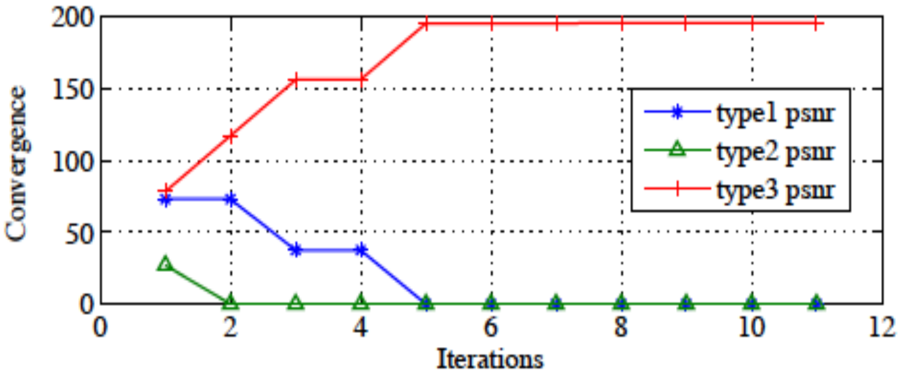
- The decomposed channel sensing problem can be solved
    - Optimally if each CU can sense all the channels
    - Optimally if each CU is not assign to more channels than its sensing capability
    - Sub-optimal with a greedy algorithm if each CU can only sense a small number of channels

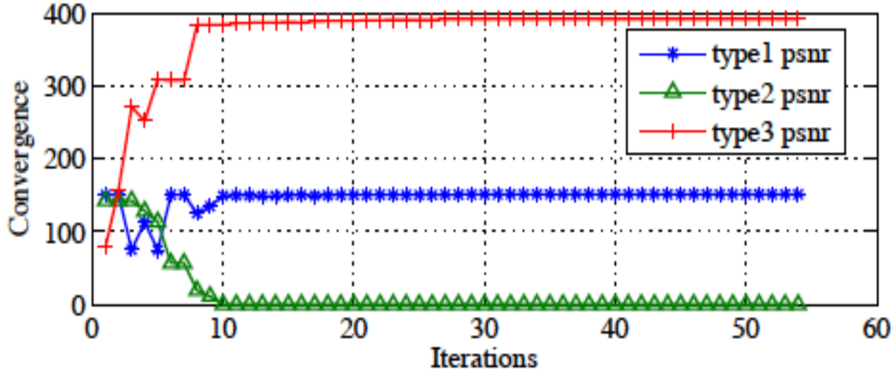
- The decomposed channel assignment and power allocation problem can be solved with a Column Generation based iterative algorithm, which is optimal

Main Results (cont'd)

- 30 channels, 30 CUs, 10 power levels, 3 video types (Suzie, Carphone, Football)







Conclusion

- Multi-user video streaming at the downlink of a cellular CR network
  - Joint sensing, access and power allocation optimization
- Our approach
  - Cross-layer optimization
  - Decomposition of the problem into a channel sensing problem and a joint channel allocation and power allocation problem
  - Maintains optimality under certain conditions
  - Developed effective solution algorithms

Open Problems

- More general spectrum sharing model and relaxed assumptions
  - Synchronized PU transmissions, synchronized SU transmissions, two state discrete-time Markov process for channel availability, common control channel
  - Unobtrusive to PUS versus involving Pus in spectrum sharing
  - Each would change the picture and may require new analytical tools
- Admission and access control
  - The lowest video quality requirement for CR users may not always be guaranteed
  - Feasibility test and limit the number of active CR users
- Existing work are mostly theoretic studies
  - It would also be interesting to develop CR video streaming testbeds [Zhang09]
  - Demonstrate the system performance under a realistic wireless environment
  - Revealing new problems with practical importance

Open Problems (cont'd)

- Quality of Service (QoS) versus Quality of Experience (QoE)
  - Need for accurate QoE models that are amenable to analysis
  - MOS evaluation dataset
- Coexistence of heterogeneous multimedia applications and coexistence with other existing and emerging wireless applications
  - A plethora of different applications that generate different types of traffic flows, all sharing the extra bandwidth harvested by CRs
  - Treat one as background traffic for the other, or
  - … develop something like the Integrated Services (intserv) and Differentiated Services (diffserv) in the Internet?
- Cross-layer multi-object optimization, MINLP problems
- Evolving CR networks: coexistence with Radar, LTE-U (4.5G), 5G wireless, spectrum auction, spectrum policy, radio map database, …

Conclusions

- Trend and need for CR video
  - A good time for wireless multimedia research
- Challenges and existing solutions
- Three case studies
  - Multicast in cellular CR networks
  - Multi-user video stream in ad hoc CR networks
  - Downlink multi-user video streaming in cellular CR networks
- Open problems
- For more details, please visit: http://www.eng.auburn.edu/~szm0001/

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Thank You!

Questions & comments?

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