New Approaches To Next Generation Communication: Cross Layer Design and IDMA

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* A joint work by Dongfeng Yuan, Haixia Zhang, Yanbo Ma and Xiaotian Zhou
Contents

- Background
- CLD in the Next Generation Communication
  - Concept of Cross Layer Design
  - CLD in Multi-media Sensor Network
  - CLD in Vehicular Communication Networks
- IDMA in the Next Generation Communication
  - Concept of IDMA
  - IDMA in Cognitive Radio Network
- Other Related Work
Next Generation Communication

- Demands of NGC:
  - Broadband Transmission
  - Multi-media Transmission
  - Supporting High-speed UT
  - Ubiquitous Experience

- Research on NGC
  - Novel Network Framework
    - Cognitive Radio, Cooperative Network, WSN, WiMAX ......
  - Novel Methodology or Technology
    - Cross Layer Design, IDMA, OFDM, Network Coding......
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Concept of Cross Layer Design

- Why Layered?
  - Simplify the network protocol design
  - Avoid the information exchange between different layer
  - Facilitate the interconnection of different devices
  - Portability in different scenario

The original model is proposed for wired network
Concept of Cross Layer Design

- **Drawbacks:**
  - Not suitable for time-varying wireless scenario
  - Independently optimization in one layer with respective to its output might lead to a counterproductive results to the other layer

- **Example:**
  - Packet loss due to fading effect in wireless scenario may be incorrect treated as congestion in traditional TCP protocol

![Diagram of Cross Layer Design](image)
Concept of Cross Layer Design

- Top down CLD
- Bottom up CLD
- Composite CLD
Concept of Cross Layer Design

- Cross Layer Model
  - Effective capacity:
    - describe the queuing behaviors at data link layer
    - characteristic the maximal arrival rate which can be supported under guaranteed delay QoS requirements
  - Mathematical expression
    \[ E_C(\theta) = \lim_{t \to \infty} \frac{1}{\theta t} \log E\left[ e^{\theta \sum_{k=1}^{t} S[k]} \right] \]
    \( S[k] \) denotes the service process
    \( \theta \) denotes the delay QoS exponent
    \[ \Pr\{D(t) \geq D_{\text{max}}\} \approx \delta e^{-\theta' \mu D_{\text{max}}} \leq \varepsilon. \]
    \( \delta \) non-empty probability of the buffer at link layer
    \( \varepsilon \) maximum delay bound violation probability
    \( \mu \) rate of source traffic flow
Concept of Cross Layer Design

- Cross Layer Model
  - Physical layer
    - resource allocation
  - Data link Layer
    - queuing
  - Cross Layer information
    - effective capacity
  - QoS requirement
    - QoS exponent
    - delay bound violation probability
CLD in Multi-media Sensor Network

- Challenge in Multi-media Sensor Network
  - Power constraint at nodes
  - Read-time transmission requirement

- Scenario considered
  - Clustered single hop network
  - MAC: TDMA

* "POWER-EFFICIENT RESOURCE ALLOCATION WITH QOS GUARANTEES FOR TDMA FADING CHANNELS" accepted by Wireless Communications and Mobile Computing
CLD in Multi-media Sensor Network

- **Resource Allocation**
  - Extend network life: reducing power dissipation while fulfilling the delay QoS requirement of multimedia flow

  - Minimizing the average transit power while satisfying delay QoS requirements

- **Improve the network capacity:** increase the network throughput with QoS requirements

  - Maximizing the effective capacity with given power constraints

Dual Problem
CLD in Multi-media Sensor Network

- Problem Formulation
  - The resource allocation is formulated as a constrained optimization problem
  - *Optimization objective:* minimizing the average transmit power of sensor node

- Constraints
  - Effective capacity: delay QoS constraint
  - Slot constraint

\[
\begin{align*}
\arg \min_{\tau(h), r(h)} & \sum_{k=1}^{K} \mathbb{E} \left[ \frac{\tau_k(h)}{h_k} \left( 2^{r_k(h)/\tau_k(h)} - 1 \right) \right], \\
\text{s.t.} & \quad -\frac{1}{\theta_k} \log \left( \mathbb{E} \left[ e^{-\theta_k r_k(h)} \right] \right) \geq E_k, k = 1, \ldots, K, \\
& \quad \sum_{k=1}^{K} \tau_k(h) \leq 1.
\end{align*}
\]
CLD in Multi-media Sensor Network

To minimize the power while fulfilling QoS requirements

Release Qos constraints and obtain the partial lagrangian function

Dual function

Dual problem: to maximize the dual function

Subgradient iteration algorithm

Outer iteration

Lagrangian dual technique

Resource allocation for the given fading state

Release the time constraint

Dual decomposition

Resource allocation for each node

Subgradient iteration algorithm

Inner iteration

Dual problem

Algorithm Flow Chart
CLD in Multi-media Sensor Network

- Rayleigh fading channel and $\theta_1 = 2, \theta_2 = 3$
- The joint power and time allocation to minimize the average power while fulfilling the given delay QoS requirements
- The power and time allocated to user 2 is larger than those of user 1 under the same channel conditions.
CLD in Multi-media Sensor Network

- The average total power versus delay QoS exponent \( \{\theta_1, \theta_2\} \)
- The average total power increase with QoS exponent
- Symmetry
CLD in Multi-media Sensor Network

- **Problem Formulation**
  - The resource allocation is formulated as a constrained optimization problem
  - **Optimization objective**: maximizing the effective capacity of network
  - **Constraints**
    - Power constraint of each node

\[
\begin{align*}
\arg \max_{\tau(h), p(h)} & \quad -\frac{1}{\theta} \log \left( E \left[ e^{-\theta \sum_{k=1}^{K} \tau_k(h) \log_2 (1 + h_k p_k(h)/\tau_k(h))} \right] \right), \\
\text{s.t.} & \quad E[p_k(h)] \leq Q_k, k = 1, \ldots, K, \\
& \quad \sum_{k=1}^{K} \tau_k(h) \leq 1.
\end{align*}
\]
CLD in Multi-media Sensor Network

To maximize the effective capacity power while fulfilling power constraints

Release Qos constraints and obtain the partial lagrangian function

Dual function

Lagrangian dual technique

Outer iteration

Dual problem: to maximize the dual function

Subgradient iteration algorithm

Inner iteration

Resource allocation for the given fading state

Release the time constraint and obtain the partial lagrangian function

The optimal power and slot allocation
CLD in Multi-media Sensor Network

- Rayleigh fading channel
- The effective capacity versus QoS exponent
- The effective capacity converges to a nonnegative constant

Wireless Mobile Communication and Transmission Lab. (WMCT)
CLD in Vehicular Communication Networks

- **Network scenario**
  - downlink channel of V2I communications
  - Physical layer: OFDM/OFDMA

- **Resource allocation**
  - allocate sub-carriers to minimize the total power consumption while still satisfying the given delay aware QoS constraints of specified application.

*“Quality-of-Service Driven Power, Bit and Subcarrier Allocation Policy for Vehicular Communication Networks”, accepted by IEEE Journal on Selected Areas in Communications (JSAC)*
CLD in Vehicular Communication Networks

- Cross-layer framework

(a) Diagram showing the integration of various layers in a vehicular communication network, including Higher Layers, Data Link Layer, Physical Layer, Subcarrier Allocation, and adaptive modulators.

(b) Diagram illustrating the process of subcarrier allocation and the use of CSI (Channel State Information) for user-specific sub-carrier information.
CLD in Vehicular Communication Networks

- Problem formulation
  - The resource allocation is formulated as a constrained optimization problem
  - **Optimization objective:** minimizing the transmit power of basestation
  - **Constraints**
    - QoS requirements; Subcarrier

\[
\begin{align*}
\min_{\Omega_k, C_{k,n}} & \sum_{k=1}^{K} \sum_{n \in \Omega_k} E \left[ \frac{1}{\alpha_{k,n}} \left( 2^{C_{k,n}} - 1 \right) \right], \\
\text{s.t.} & \quad -\frac{1}{\theta_k} \log \left( E \left[ e^{-\theta_k T_j B_N \sum_{n \in \Omega_k} C_{k,n}} \right] \right) \geq E_v^k, \forall k, \\
& \quad C_{k,n} \geq 0, \forall k, n, \\
& \quad \Omega_1 \cup \Omega_2 \cup \ldots \cup \Omega_K \subseteq \{1, 2, \ldots, N\}, \\
& \quad \Omega_i \cap \Omega_j = \emptyset, \quad i \neq j.
\end{align*}
\]
CLD in Vehicular Communication Networks

- **Time-sharing**
  - Time-sharing: release the integer variable
  - With two new variables the problem is converted into a convex optimization problem

\[
\begin{align*}
\arg\min_{\rho_{k,n}, R_{k,n}} & \sum_{k=1}^{K} \sum_{n=1}^{N} \mathbb{E} \left\{ \frac{\rho_{k,n}}{\alpha_{k,n}} \left( \frac{R_{k,n}}{2\rho_{k,n}} - 1 \right) \right\}, \\
\text{s.t.} & \quad \mathbb{E}\left\{ e^{-\theta_{k} R_{k,n}/N} \sum_{n=1}^{N} C_{k,n} \right\} \leq e^{-\theta_{k} E_{c}^{k}}, \\
& \sum_{k=1}^{K} \rho_{k,n} = 1, \forall n, \\
& R_{k,n} \geq 0, \forall k, n, \\
& 0 \leq \rho_{k,n} \leq 1, \forall k, n.
\end{align*}
\]

- **Time-sharing:**
  - Time sharing factor $\rho_{k,n}$
  - $R_{k,n} = \rho_{k,n} C_{k,n}$
To minimize the power while fulfilling QoS requirements

Release QoS constraints and obtain the lagrangian function

KKT optimality conditions

The optimal power policy

Sub-carrier Allocation Algorithm

\[
L(\rho_{k,n}, R_{k,n}, \lambda_k, \mu_n, \xi_{k,n}) = \sum_{k=1}^{K} \sum_{n=1}^{N} E \left[ \frac{\rho_{k,n}}{\alpha_{k,n}} \left( \frac{R_{k,n}}{2^\gamma_k} - 1 \right) \right] - \sum_{n=1}^{N} \mu_n \left( \sum_{k=1}^{K} \rho_{k,n} - 1 \right) + \sum_{k=1}^{K} \lambda_k \left[ e^{-\rho_{k,n}^* T_k B N \xi_{k,n}} - e^{-\rho_{k,n}^* T_k} \right] - \sum_{k=1}^{K} \sum_{n=1}^{N} \xi_{k,n} R_{k,n},
\]

\[
\frac{\partial L(\rho_{k,n}, R_{k,n}, \lambda_k, \mu_n, \xi_{k,n})}{\partial R_{k,n}^*} = 0.
\] (1)

\[
\frac{\partial L(\rho_{k,n}, R_{k,n}, \lambda_k, \mu_n, \xi_{k,n})}{\partial \rho_{k,n}^*} = 0, \quad \text{if } \rho_{k,n}^* \in (0,1)
\]

\[
< 0, \quad \text{if } \rho_{k,n}^* = 1
\] (2)
CLD in Vehicular Communication Networks

- Minimized power versus the delay QoS exponent
- The performance gain in power efficiency increases with the QoS exponent

- Subcarrier $N = 32$, users $K = 2$
- Subcarrier bandwidth $B_N = 10$ kHz, $T_f = 2$ ms
CLD in Vehicular Communication Networks

- The performance gain in power efficiency increases with the QoS exponent

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Concept of IDMA

- Interleave Division Multiple Access
  - Interleaver is the mean to distinguish different user
  - Low cost detection based on Gaussian approximation
  - SCM & High spectral/power efficiency
Concept of IDMA

- Gaussian Approximated Detection

  \[ r(j) = \sum_{k=1}^{K} h_k x_k(j) + n = h_k x_k(j) + \zeta_k(j) \]

- Estimate:
  \[ e_{ESE}(j) = 2h_k \cdot \frac{r(j) - E(\zeta_k(j))}{Var(\zeta_k(j))} \]

- Decode:
  \[ e_{DEC}(x(j)) = C^{-1}(\lambda_{ESE}(x(j))) - \lambda_{ESE}(x(j)) \]
IDMA in Cognitive Radio*

- Cognitive Radio Scenario
  - Overlay
  - Underlay:
    - Primary User (PU) and Secondary User (SU) cannot coexist on the same frequency

- Challenges
  - There exists certain interference period due to the delay of sensing
  - SU link is easily interrupted by the re-appearance of PU

IDMA in Cognitive Radio

- CORVUS Model
  - Sub-channel of one SU link should be scattered among different F-bands
  - Save redundant sub-channels to keep the maintenance of SU link
IDMA in Cognitive Radio

- **Drawbacks of CORVUS**
  - Heavily loaded scenario: no longer effective to alleviate the mutual interference
  - Spectrum waste: Reserving redundant sub-channels
  - The narrow bandwidth of sub-channels

**Orthogonal MA Scheme → Non-orthogonal MA Scheme**
IDMA in Cognitive Radio

- **IDM-CORVUS**
  - Broadband property of IDMA: the secondary user enjoys the whole bandwidth of these F-bands
  - Reserving redundant interleavers: keep the SUL maintenance during PU reappearance without introducing the spectrum waste
IDMA in Cognitive Radio

- SU link:
  - Each SU is equipped with L interleavers, where L is the number of available F-bands.

\[
x_k(j) = \sum_{l=1}^{L-L_{red}} x_l(j) \cdot \exp(i\theta_l)
\]

- \( L_{red} \) : the number of redundant interleavers.
- \( \exp(i\theta_l) \) : modulation factor due to the l-th F-band
IDMA in Cognitive Radio

- Tradeoff between Reliability and Throughput

\[ x_k(j) = \sum_{m=1}^{\alpha(L-L_{red})} x_m(j) \cdot \exp(i\theta_m) + \sum_{n=\alpha(L-L_{red})+1}^{L-L_{red}} x_n(j) \cdot \exp(i\theta_n) \]

- \( \alpha \): Multiplexing factor
- Reliability: Sending same data stream through M layers
- Throughput: Sending different data through N layers
IDMA in Cognitive Radio

Simulation Results

- Rate of repetition
  - code=1/32
- Iteration number 15
- Equal power allocation
- 3 interleavers per user
- 1 redundant interleaver per user
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Other Related Works

- **Books:**
  - “Cross Layer Design: From Theory to Application” (Chinese Version), published by posts & Telecom Press.

- **Papers:**
  - Game theoretic CLD in Multi-media Sensor Network
Other Related Work

- **Papers:**
  - **CLD in Cognitive Radio**
  - **IDMA in Cooperative Network**
    - “A Multi-source Cooperative Scheme based on IDMA aided Superposition Modulation,” *submitted*
  - **IDMA in Common Frequency Network**
    - Inter-cell interference cancellation
Thanks
For Your Attention!

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