Cross Layer Design: MAC/PHY Convergence for the Ultimate Radio Resource Management

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Tutorial 2

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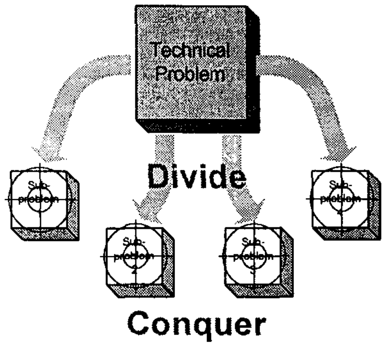
목 차

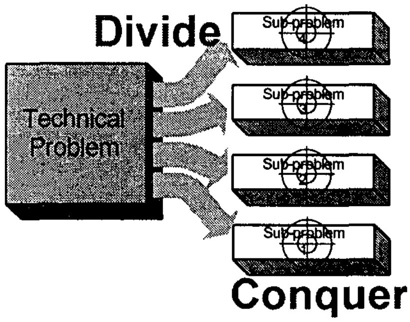
Layering Concept

- Layering is a general design concept in S/W and H/W engineering.
- Special case of Divide-and-Conquer(-and-Merge) approach

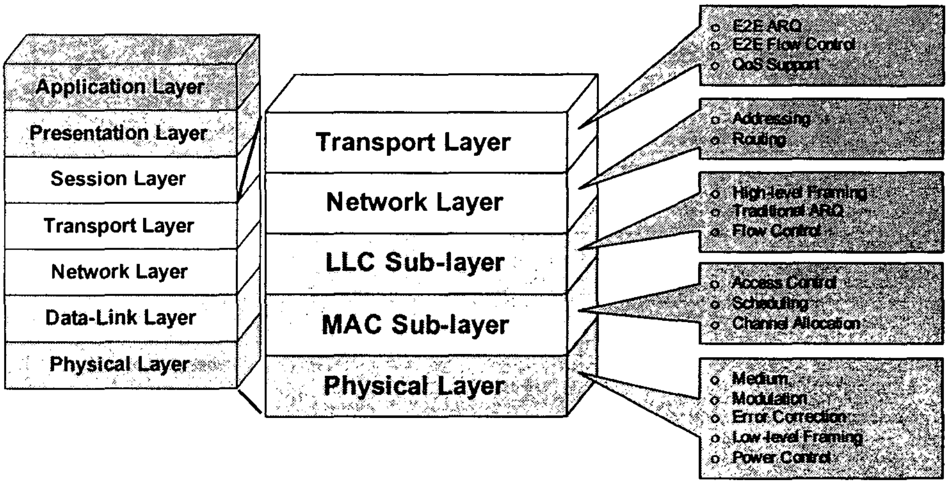


Layering Concept

- Layering is D-C-M applied in the vertical direction.
  - Low-level solution will serve higher-level solution.
- Advantage
  - Simpler and more focused technical problems
  - Improved compatibility and associativity
  - Independence among solutions
  - Facilitated standardization processes
- Disadvantage
  - Sub-optimal performance



Traditional 7 Layer Architecture

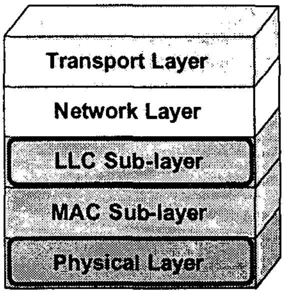


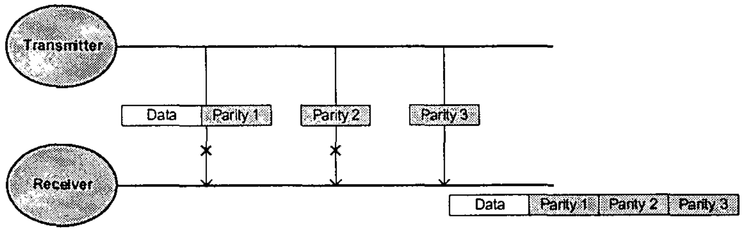
Cross-Layer Design

- Definition
  - System design principle or methodology addressing technical problems in more than one layers simultaneously.
- Is it a new concept?
  - No, it has been around for a while (whether we recognized them as "cross-layer design or problem").
  - Example
    - When we design a MAC sub-layer, we take the key properties of the PHY layer into account, and vice versa.
    - When we design PHY/MAC/LLC layers, we keep the target applications in mind all the time.
- Why so much enthusiasm about it then?
  - Evolution of communication/network systems brought up several "fatal" or "major" weaknesses of traditional layering!
    - Wireless links for data communication and packet switching.

C-L Design Example : Hybrid ARQ

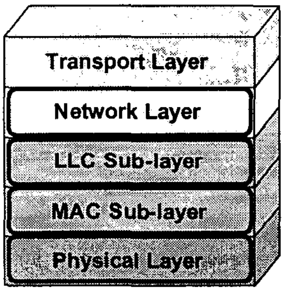
- Cooperation between
  - ARQ function (LLC)
  - Error Correction function (PHY)
  - Adaptive Mod./Coding function (PHY)
- Will not discard partially delivered frames.
- Improves the throughput and resource efficiency.

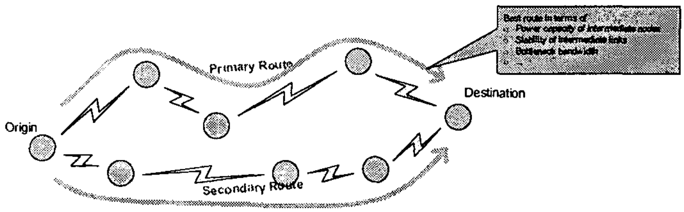




C-L Design Example : Ad hoc Routing

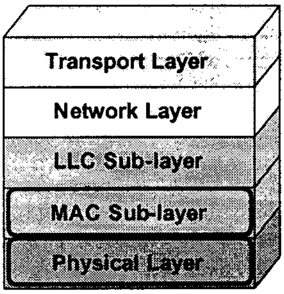
- Cooperation between
  - Routing function (NET)
  - Connection setup/management (LLC)
  - Dynamic Channel Sharing (MAC)
  - Power control function (PHY)
- Establish/manage one or multiple route between transmitter/receiver node pairs for the best
  - Reliability
  - Power consumption
  - Resource efficiency

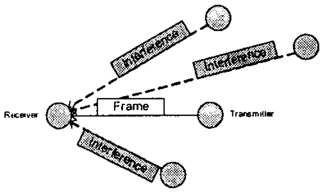




C–L Design Example : Multi–Capture MAC

- Cooperation between
  - Random (or scheduled) access function (MAC)
  - Power control function (PHY)
  - Error correction function (PHY)
- Collisions between frames may be overcome in wireless environments.
  - Not just avoid but control the pattern of collisions
  - Improve the throughput/efficiency by allowing multiple transmissions

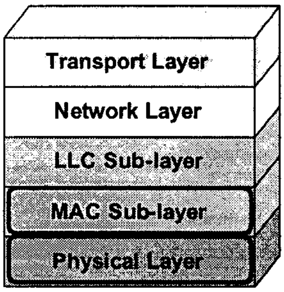


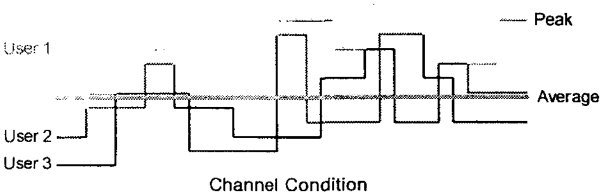


# of interfering frames	0	1	2	3	4	5
Capture probability	0.98	0.65	0.53	0.34	0.23	0.20

C–L Design Example : Opportunistic Scheduling

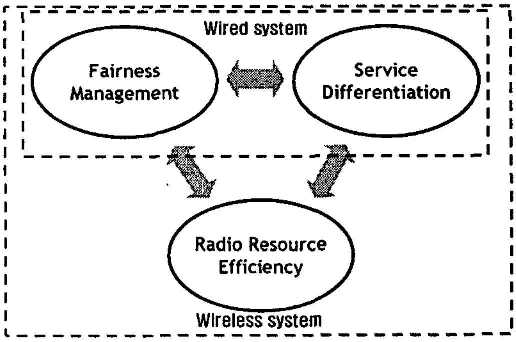
- Cooperation between
  - Scheduling function (MAC)
  - Adaptive Modulation/Coding function (PHY)
- Resource is allocated to a user (or session) when it is most valuable to it.
- System–wise efficiency can be improved significantly.
- Surfers love brutal waves, while fishers don't.



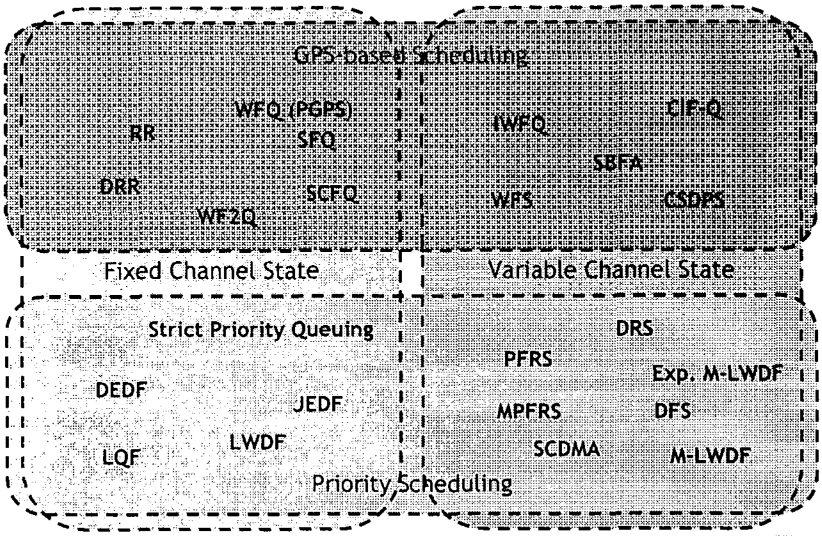


Scheduling Function

- Definition
  - Resource allocation along the time axis
  - Determines when resources will be allocated to each user or session.
- Objectives

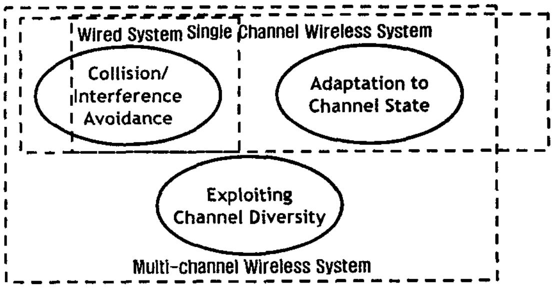


Scheduling Schemes

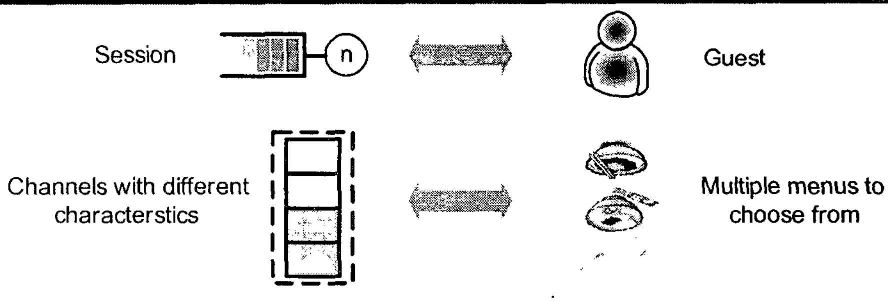


Channel Allocation (CA) Function

- Definition
  - Resource allocation along the channel axis
  - Determines which resource block will be allocated to each user or session.
  - May be considered as a microscopic part of RRM function.
- Objective



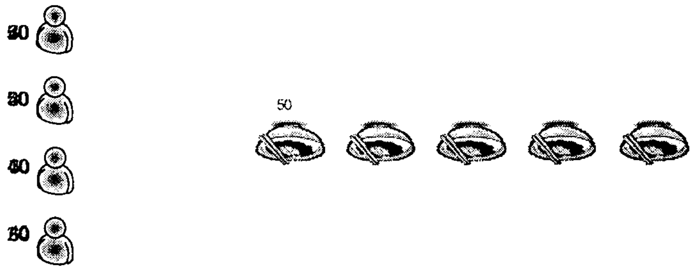
Analogy to Meal Distribution



- A scheduling/CA problem is very much like distributing meals to multiple guests in a restaurant.
  - Guests may have different appetite and preference for meals.
  - There are only finite number of meals that can served in a time period.

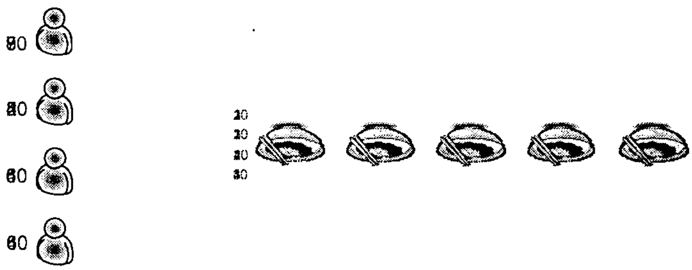
Wired System

- Nature of problem
  - There is only one menu to choose.
  - A meal gives exactly same satisfaction to every guest.
  - The marginal satisfaction does not change with time.
- Solution
  - Deliver meals in the order of appetite.
  - Avoid unfair distribution.



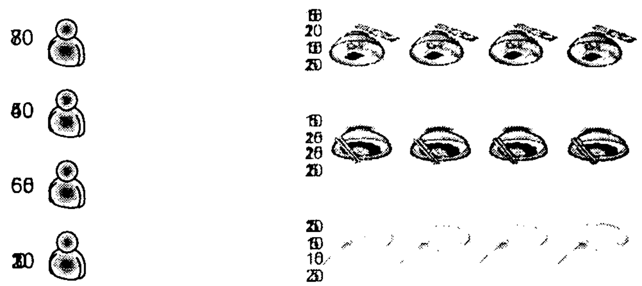
Single-Channel Wireless System

- Nature of problem
  - There is only one menu to choose.
  - A meal may give different satisfaction to different guests.
  - The marginal satisfaction changes with time.
- Solution
  - Deliver meals in the order of appetite.
  - Deliver meals to who will get the most satisfaction.
  - Avoid unfair distribution.



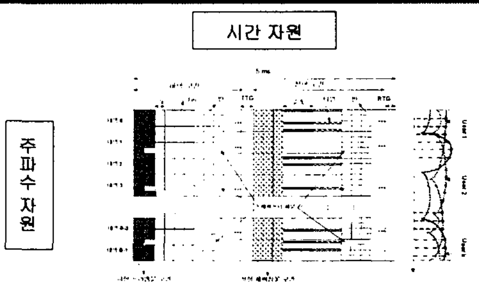
Multi-Channel Wireless System

- Nature of problem
  - There are multiple menus to choose from.
  - Different meals may give different satisfaction to different guests.
  - The marginal satisfaction changes with time.
- Solution
  - Deliver meals in the order of appetite.
  - Deliver meals to who will get the most satisfaction.
  - Avoid unfair distribution.

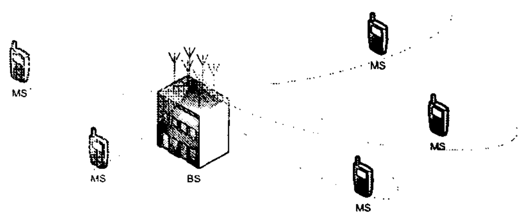


Multi-Channel Wireless Systems

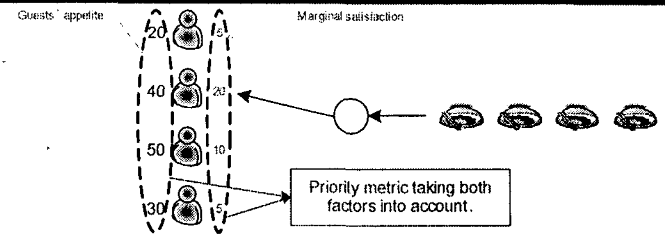
- OFDMA



- MIMO (SDMA)



Traditional Single-Channel Scheduling/CA Model



- What is given?
  - Guests' appetite level
    - *Corresponds to the urgency based on QoS/fairness requirements.*
  - Marginal satisfaction of a meal to different guests
    - Corresponds to the data rate achievable by an AMC with current channel states of users.
- What needs to be done?
  - Priority metric for each guest will be computed from its appetite and marginal satisfaction.
  - Meals will be delivered in the order of the priority metric, in such a way that the overall satisfaction of guests can be maximized.

⇒ Opportunistic Scheduling to maximize multi-user diversity!

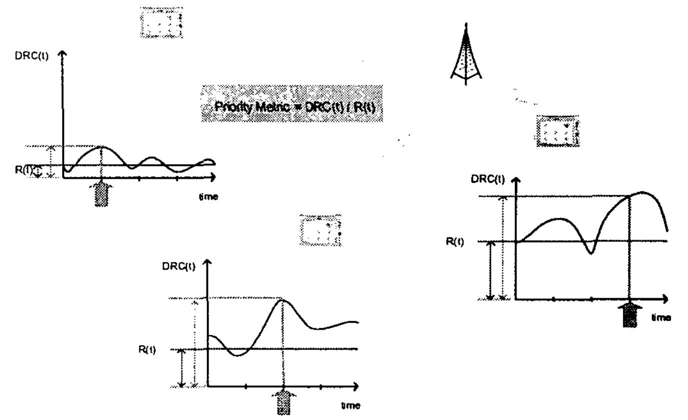
Proportional Fair (PF) Scheduler

- 각 사용자 *i*에 대해 매 시간 *t*에 다음을 계산.

$$\frac{r_i(t)}{\bar{r}_i(t)}$$

  - $r_i(t)$: current data rate
  - $\bar{r}_i(t)$: average data rate
  - Average data rate의 계산은 일반적으로 auto-regressive 평균값을 사용함
- $\frac{r_i(t)}{\bar{r}_i(t)}$ 가 가장 큰 사용자부터 선택 전송

Proportional Fair (PF) Scheduler



- Opportunistic scheduling의 대표적 형태
- 평균 대역폭에 비례하는 성능

Modified Largest Weighted Delay First

- M-LWDF scheduler
  - 매 slot 또는 frame에서 다음의 수치를 최대로 하는 사용자의 패킷을 선택하여 전송

Service weight of user *i* for service differentiation

Reflects the channel quality of user *i*

Reflects the urgency level of user *i*

$$\text{priority metric} = \gamma_i r_i(t) W_i(t)$$

where

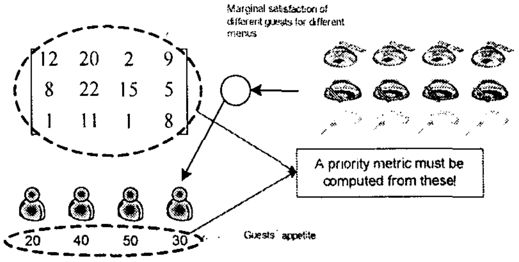
$\gamma_i = a_i / \overline{r_i}(t)$

$a_i = -\log \delta_i / T_i$

$W_i(t) = k_i(t) / t_i(t)$

$r_i(t)$: data rate supported by the channel
$W_i(t)$: Waiting time of user i at time t
$k_i(t)$: Token of user i at time t
$t_i(t)$: Token rate of user i at time t
δ_i : maximum probability of exceeding the delay threshold
T_i : delay threshold

Problems of Multi-channel Scheduling/CA



- What is given?
  - Guests' appetite level
  - Marginal satisfaction of different menus to different guests
    - Given as a matrix.
- What needs to be done?
  - Priority metric for each guest must be computed from its appetite and marginal satisfaction for different menus.
  - Meals will be delivered in the order of the priority metric, in such a way that the *overall satisfaction of guests can be maximized.*

⇒ A chicken-and-egg problem arises!

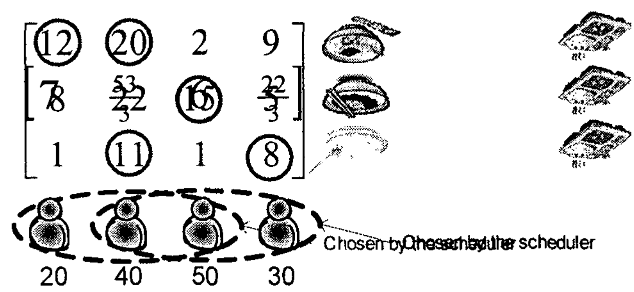
Chicken-and-Egg Problem in M-C Scheduling/CA

Total satisfaction = 43

Total satisfaction = 38

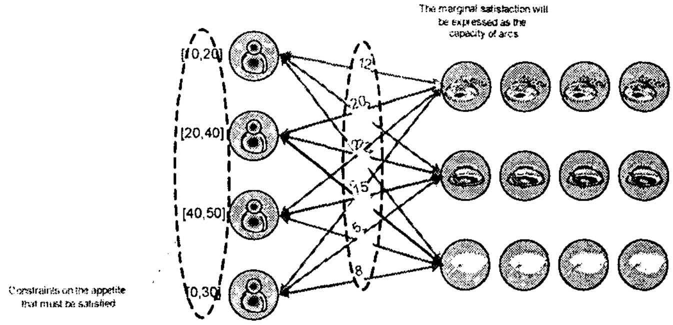
Total satisfaction = 31

Total satisfaction = 30.67



- None of scheduling and CA can be carried out first!
  - The priority metric can be computed once the menu is determined.
  - The menu can be determined once guests are chosen for serving meals.
- What if we mix all the menu make things easy (so called channel diversity)?
  - Overall satisfaction will decrease!

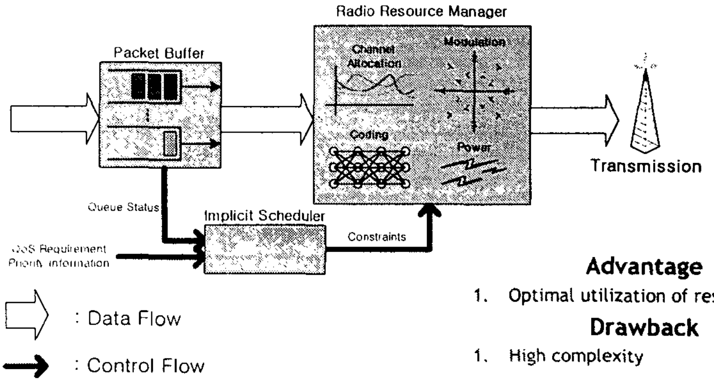
Optimal Multi-Channel Scheduling/CA



- Optimal Matching Problem
  - The amount of appetite than must be satisfied in the current turn will be given as constraints.
  - The marginal satisfaction that a menu can provide to a guest will be considered as the capacity of the corresponding arc.
  - The problem is then to find a set of arcs that maximizes the total satisfaction under the constraints.

Optimal Multi-Channel Scheduling/CA

- CA tries its best only to maximize the throughput.
- Scheduler imposes constraints to CA.
  - Implicit ordering of transmission



Advantage

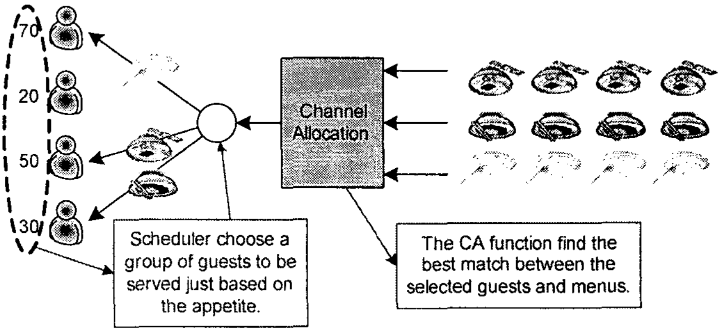
1. Optimal utilization of resources

Drawback

1. High complexity

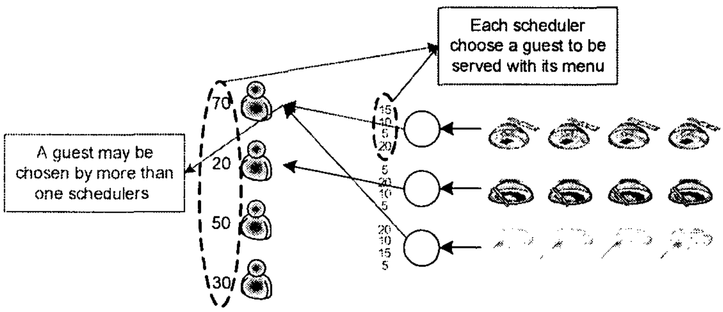
Practical Approaches (Group Scheduling)

- A scheduler chooses a group of guests.
  - Takes the appetite of guests into account
- The CA function maximizes the satisfaction.
  - Try to match guests (in the buffer) and menus in such a way that the total satisfaction is maximized.

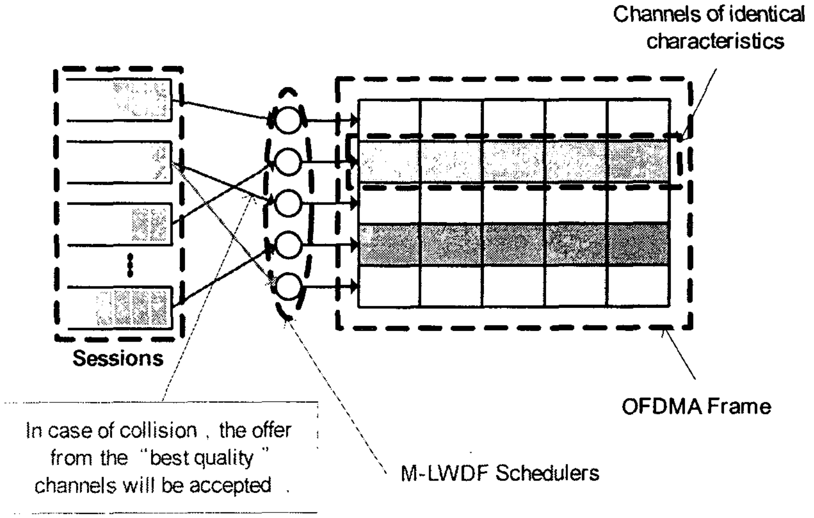


Practical Approaches (Parallel Scheduling)

- Each scheduler is responsible for distributing a single menu of meals.
  - The chicken-and-egg problem can be avoided because each scheduler knows which menu will be delivered to the guest it chooses.
- A guest may be chosen for multiple menus.
  - An arbitration mechanism is required to cope with the collision between schedulers.



Example of Parallel Schedulers



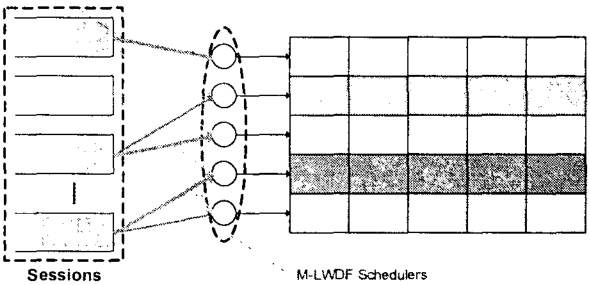
3-Phase Extension of Parallel Schedulers

- Parallel Scheduling does not really exploit multi-channel diversity.
- To fully exploit multi-channel diversity, 3-phase scheduling is introduced.
  - Sessions will first apply for "good" channels.
  - Schedulers will do their job only for their applicants.

Request Phase
Each session chooses multiple "good" channels that it want to be allocated

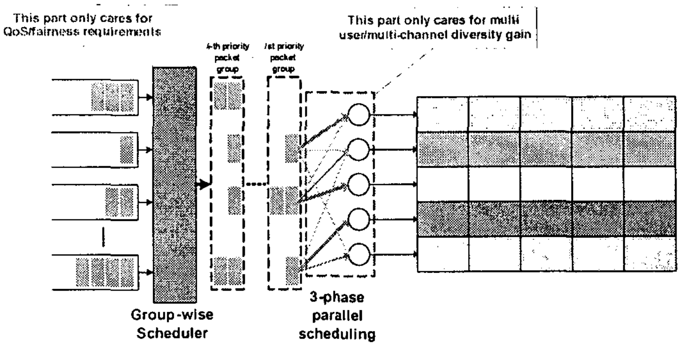
Grant Phase
Each scheduler chooses one session to which its channel will be allocated

Accept Phase
Sessions choose one of the grants that it received, and load its data to the corresponding channel



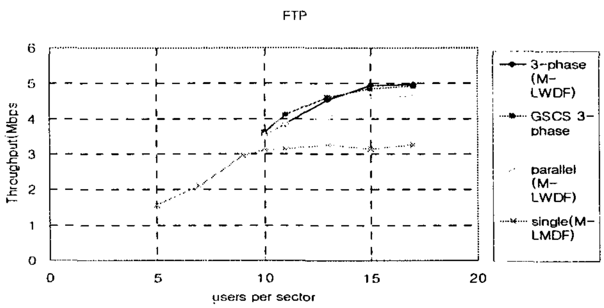
Group-wise Scheduling for QoS Support

- Deriving a priority metric reflecting both resource efficiency and QoS/fairness requirement limits our selection of scheduling rules.
- Two functions can be split through group-wise scheduling
  - First block cares for QoS/fairness.
  - Second block exploits multi-user/multi-channel diversity.



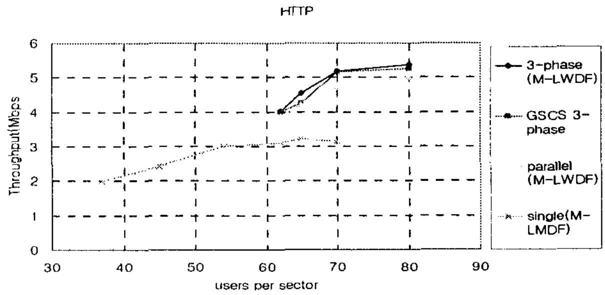
Numerical Example

- Environment
  - WiBro-based OFDMA system
  - FTP only
- Results
  - Original parallel scheme, 3-phase extension, group-wise extention show about 43%,52%,51% efficiency improvements with respect to single-channel scheme
  - 3-phase extension shows improvement of 6.8% over the original parallel scheme.



Numerical Example

- Environment
  - WiBro-based OFDMA system
  - HTTP only
- Results
  - Original parallel scheme, 3-phase extension, group-wise extention show about 51%,64%,63% efficiency improvements with respect to single-channel scheme
  - 3-phase extension shows improvement of 8% over the original parallel scheme.



Why Cross-Layer Design?

- Single-layer technology has nearly reached the ultimate performance.
  - Can we improve bps/Hz·m^2 of a wireless system only digging into a fabulous modulation/coding/transmission technology?
- Few single-layer technique will fully realize its potential without the assistance of other layer technology.
  - Will just deploying relays automatically improve the capacity of cellular system?
  - Now, the WiBro service will soon launch. Will its technical superiority guarantee its commercially success?
- Pretty much everyone in communication/networking field are fed up struggling with stupid layer-based standards designed for its own sake.
  - To design an entirely thorough communication system, engineers for all layers have to put their heads together from the beginning.
  - Or at least, a few of them have to.