Week 1

Meeting: discussed the project timeline

obtained the 'noise & signal' and corresponding simulation tutorial

Outcome: revised MATLAB operations

built Q-function with predefined function 'erfc'

plotted analytical BER vs E_b/N_0 for unipolar NRZ

forked it to bipolar NRZ and compared the result

problem: changed the design of Q-func rather than the main function (found and corrected in wk 2)

Week 2

Meeting: Q-func problem pointed out

discussed the physical meaning of Q-func (error probability)

obtained materials about fading and optimum receiver

Outcome: corrected the Q-func

learned fading channel model: Rayleigh Fading (distribution. signal detection. BER and MATLAB implementation)

compared AWGN channel & Rayleigh channels in terms of BER vs. E_b/N_0

Problem: understanding the threshold

$$V_T = \frac{E_0 + E_1}{2} \quad \text{or} \quad \left| \frac{E_1 - E_0}{2} \right| \ ?$$

thought to be the previous one.

Wk 3:

Meeting: explained my understanding to form-I receiver

discussed requirements, keypoints and must-haves of the preliminary report

got the slides of signal space.

Outcome: finished the abstract and introduction parts

generated the multi-path fading channel (Rayleigh fading IR + FFT)

Problem: why 6×6 gain became 64×6 after 64-point FFT? what's the physical meaning? What does 64 stand for?

Week 4:

Meeting: discussed the problems about the threshold: should be the difference. (same idea but we don't consider the actual base value)

got MATLAB tutorial set

Outcome: understood the optimum receiver form-I (map/cast to basic signal sets and compare)

simulated the NRZ & RZ BER vs Eb/No with Monte-Carlo method. compared with the theoretical value.

skimmed through MATLAB 1-6

problem: cannot understand form-II receiver

Week 5

Meeting: discussed the form-II receiver:
need to know signal space first

asked the question about FFT:
FFT point = number of points
in frequency = number of subcarriers

got all the remaining slides of
wireless comm.

Outcome: debugged the design of Rayleigh
fading channel (h's generated independently
for different channels)
Planned the timeline and corresponding
cornerstones

designed the Gantt Chart for the
project

Problem: need to know signal space

Week 6

Meeting: showed the results of the Rayleigh fading channel: problem about the scale pointed out (the total power of all paths should be normalised to 1)

Outcome: fixed the problem above by multiplying the IR by scaling factor

studied the signal space

Problem: how to determine basis signals?

in Cardinal coordinate, 2 points → 1-D. 3 points → 2-D ..., why in signal space we can have 2 points → 2-D ?

why the energy of basis signal is 1 rather than the length?

Week 7

Meeting: determining basis signals: mapping or GSO procedure

signal space: predefined for easy signal implementation

energy rather than length: we want reflect the difference of energy.

Outcome: Understood OFDMA and its' pros & cons compared with FDMA, TDMA and CDMA (b/w efficiency). Memorised the structure of OFDM transmitter and receiver

Problem: How has the original msg been changed during process?

What's the difference between ISI, IBI and ICI?

why for CP we need to repeat the info to make blocks orthogonal? what if we leave it blank?

Week 8

Meeting: original dealt with for subcarriers to convey.

CP: avoid ISI. if left blank, the two adjacent block won't be orthogonal.

Outcome: maximum capacity subcarrier allocation (For each sc., compare the corresponding gain for every user and assign it to the one with maximum gain. Finally remove it from the available sc. set).

Problem: now the number of sc. = user. generally it should > user. the algorithm should be improved later.

some user cannot get sc. in a certain slot with MC allocation. Is this right? If not, how to ensure MC and allocate those users with scs?

Week 9:

Meeting: N_sc > N_user, but just assume they equal now.

There are some users without scs in a certain slot to reach MC.

Outcome: Simulated the avg. data rates for channels for MC & random subcarrier allocation.

began to design water-filling algorithm.

Problem: —

Week 10

Meeting: asked the idea and design of WF.

not fully understood the iteration and suggested to read relevant reference.

Outcome: designed a demo of WF power allo-cation scheme but the result is not as anticipated: the overall channel power is not 1.

read through the reference but cannot get the point.

Problem: the channel power is not 1 as ex-pected.

Still not understand the steps of WF algorithm.

Week 11

Meeting: the SCs with neg. power need to be removed from the available set and the SC. number should be updated after one cycle of channel.

The result should be iterated and calculate again if there are un-available SCs.

Keep repeating the steps above until all available SCs are allocated with power ≥ 0.

Outcome: fixed the WF algorithm. ($\Sigma P = 1$ ✓)

Compared the data rate with equal power allocation ($P_{sc} = \frac{1}{N\_sc}$)

Combined the subcarrier allocation schemes (random / MC) with power allocation schemes (equal / WF), reflect the result by channel data rate designed the slides and prepared for the project presentation

Problem: —

Week 12

Meeting: no meeting (presentation)

Outcome: delivered a presentation about the project intention, possible outcome, applications and progress so far

Problem: what's the case in real-world?

whether the ISPs have similar schemes?

Week 13

Meeting: explained the progress so far and discussed the following plans.

Outcome: learned the information about the structure of MAC layer: packet size, slot, packet arriving interval, QoS, etc.

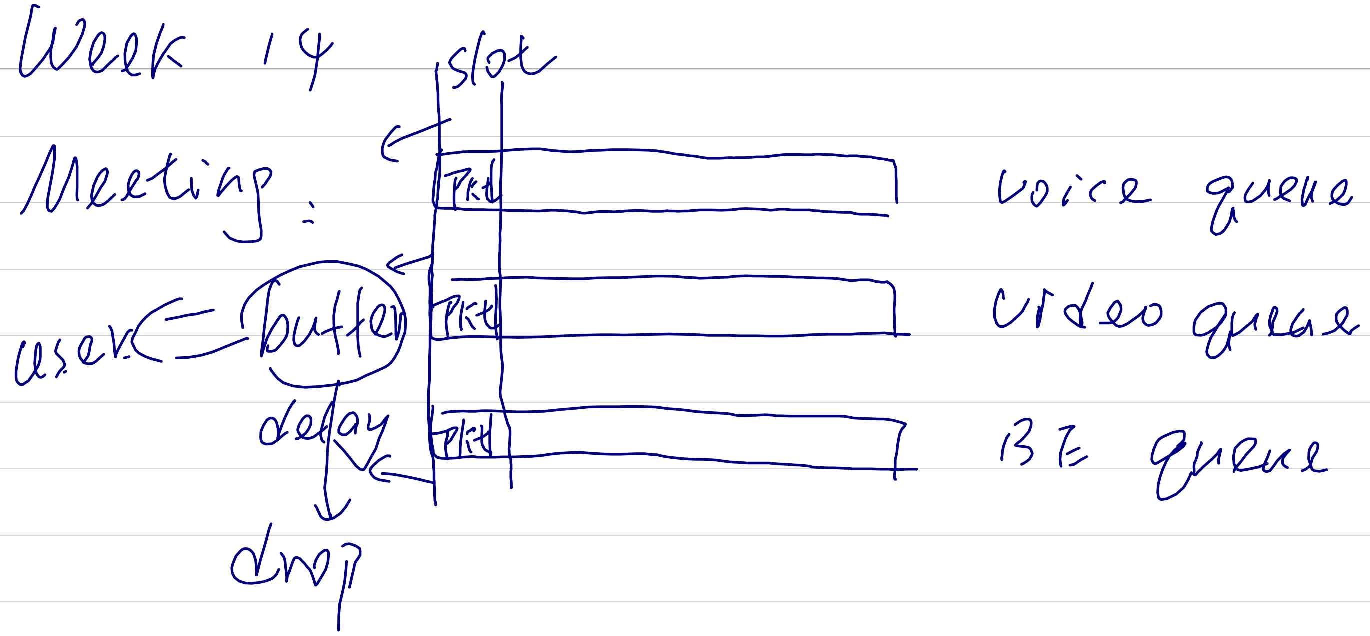
read the reference and understood the ideas of M-LWDF & PD: queue based and packet based

Problem: relationships between queues and packets?

how can slots be linked to packets and queues?

Week 14

Meeting:



Outcome: finished the weight design func. for M-LWDF

began to design weight on packet based, with size. delay. QoS, etc.

Problem: have no idea about the real delay calculation

Week 15

Meeting: Delay is already derived in pkt weight design. So don't need to consider it again.

Outcome: Fixed the M-LWDF weight design (use updated raw data to calculate the queue weight)

designed the demo for PD scheduling

Problem: PD : delay obtained when designing packet weight.

M-LWDF: how to determine delay?

Week 16

Meeting: showed the weight design of 2 scheduling schemes.

M-LWDF: calculate the time duration that a packet in buffer.

Outcome: improved the PD weight design (fixed the logic problem of the sequence of checking packet number, allocate weight & update data)

Problem: if we use the method for M-LWDF to calculate delay for PD, we got 2 different schemes to calculate delay. will they be the same?

WK 17:

No meeting (Judy away)

Outcome: combined the weight design of M-LWDF & PD with SC & power allocation (MC. WF), then obtained MWC & CWF algorithm.

created main functions, called the resource allocation demo func in every slot, which uses the result of weight design functions.

main → RA $\underset{\text{weight delay}}{\overset{\text{data pkt info}}{\rightleftarrows}}$ DS

Problem: Previous work considered weights only for [100 75 50] pkts for voice, video & BE. but the delay tolerance is [100 400 1000]. Does it mean for BE pkt with delay = 500, we don't calculate its weight?

Wk 18:

No meetings (Judy away)

Outcome: fixed the problems by setting weight pkt number: tolerance.

simulated the avg. voice. video delay and system throughput based on different schemes.

designed the poster and prepared for the inspection.

Problem: ~

previous research:

1. utility theory for RA + DS.
2. joint design of multiuser subcarrier.
   bit + power allocation.
3. integrated design of power control
   (by algorithms) subcarrier allocation
   packet scheduling
4. choose best channel gain for each user (RA)
   water-filling algorithm (PA)
5. proportional rate constraints (RA)
6. fairness criterion based on QoS satisfaction.
   channel state information
   QoS requirement
   random packet arrivals
   queue stats
   ⇒ RA
7. serial scheduling (voice > data),

Procedure:

1. downlink TDD OFDM with multiple heterogeneous traffic queues for users.

2. PD scheduling (MAC) to determine packet transmission order.
(weight ~ delay. size. QoS priority)

3. user based RA (PHY) to maximize WSC.
Choose number of packets properly to simplify.

AWGN channel

characteristics:

1. constant spectral density.
2. Gaussian distribution of amplitude.

Pdf: $S_x(f) = \frac{N_0}{2}$ W/Hz

Fading channel (diffraction. reflection. scattering)

multipath fading
shadowing
propagation loss

Large-scale path loss
→ reduction of signal strength.

small-scale fading
→ variations of density of field on specific location.

fading $\begin{cases} \text{channel gain} \\ \text{phase} \end{cases}$

CIR for multipath fading channel:

$$f(t) = \sum_{n=0}^{L-1} f_n \delta(t - \tau_n)$$

L - number of paths
f_n - channel gain
τ_n - channel delay

overall CIR (including T+R filters)

$$h(t) = \sum_{n=0}^{L-1} f_n g(t - \tau_n)$$

$g(t)$ - CIR of T+R filters

RMS spread (time dispersion of m-channels)

$$\sigma = \sqrt{\frac{\sum_n f_n^2 \tau_n^2}{\sum_n f_n^2} - \left(\frac{\sum_n f_n^2 \tau_n}{\sum_n f_n^2}\right)^2}$$

coherence bandwidth ($\Delta f < B_c \Rightarrow$ fades correlated)

$$B_c = \frac{1}{5\sigma}$$

flat fading : $\left| \begin{array}{l} B_c > B_s \\ \sigma < T_s \end{array} \right.$

all frequencies have similar channel gain + linear phase.

(single channel fading)

Rayleigh fading (no LOS)

amplitude envelope of complex channel response:

$$P(|f_n|) = \frac{2|f_n|}{\Omega} e^{-\frac{|f_n|^2}{\Omega}}$$

$|f_n|$ - pdf of channel gain
Ω - mean power of channel response

BER:

$$P_e = \int_0^\infty P_e(r) f(r) dr$$

γ - RX signal $\frac{E_b}{N_0}$
$f(\gamma)$ - probability function.

f-selective fading $\left\{ \begin{array}{l} B_c < B_s \\ \sigma > T_s \end{array} \right.$

different frequency components suffer uncorrelated fading.

(multiple fading channels)

TDD: asynchronism (adjust uplink/downlink)

achievable total data rate of user k:

$$R_k = \sum_{n \in \Omega_k} \frac{B}{N} \log_2 (1 + P_{k,n} \gamma_{k,n})$$

channel-to-noise power ratio

$$\gamma_{k,n} = \frac{|h_{k,n}|^2}{N_0 \cdot \frac{B}{N}}$$

B - bandwidth

K - users

N - subcarriers

Ω_k - index set of the subcarriers to user k

$P_{k,n}$ - power allocated to user k on subcarrier $n \in \Omega_k$.

$h_{k,n}$ - corresponding channel gain

N_0 - psd of AWGN.

OFDM:

1. zero ICI.
2. high spectrum efficiency.

Procedure:

1. map the msg. bits into symbols (BPSK. QAM)
2. convert into N parallel stream (S/P).
3. N symbols carried by different subcarriers and symbol period extended $T_{symbol} = N \cdot T_s$ ($f_{symbol} = \frac{B_s}{N}$. eliminates ISI!)
4. signal suffer flat fading.
5. CP added to avoid IBI.
6. FDE on each subcarrier independently (ZF)

Zero padding:

Adding zeros to end of a timedomain signal to increase its length.

real-time TX: delay ×
error ✓

non-real-time TX: delay ✓
error ×

PHY: TX raw bits from machine to another.
(provide CSI for upper layers)

MAC: control access to shared channel.
(control data transmit or not)

Wireless comm: m-fading, shadowing, other interference ⇒ higher BER ⇓ Cross-layer design (joint optimization)

QoS → broadband
jitter
delay
packet drop rate reductions
→ resource management on services

MAC: PD scheduling scheme determines the packet TX order by weight assignment for each packet.

PHY: summation of assigned weights of packets for each user (RA).

RA: a subset of subcarriers is allocated to each user and the number of subcarriers should be scheduled by the system.

subchannel: a group of subcarriers as a basic unit of RA in OFDM.

subcarrier allocation: allocating the subcarrier for the highest spectrum efficiency.

→ best CNR for each user.
increased system capacity.

power allocation: independent on subcarriers.

→ better system performance.

RA schemes:

1. maximize sum capacity
   (allocate resource according to best channel gain)
   → water filling algorithm: loss of fairness
   → proportional fairness coefficient: QoS unconsidered.

2. minimize overall transmit power (R.BT; R constraints)
   (Margin adaptive)

3. maximize each user's error free capacity (P_{TOT} constraint)
   (Rate adaptive)

4. maximize the worst user's capacity
   (max-min optimization)

Power allocation:

1. equal power allocation for each subcarrier.
   P: low complexity + single implementation
   C: can't adopt to changing environment.
   can't improve system performance.

2. joint (consider CSI + power simultaneously)
   C: hard to solve with non-linear constraints
   complex to find the optimal solution with large number of subcarriers.

3. substep (subcarrier, power allocations separately)
   1) equal power allocated for each subcarrier
   2) power allocated again according to the results of subcarrier allocation.

   P: low complexity
   C: only suboptimal solution.

1) C maximized only when users have enough data.

2) RA doesn't depend on QoS requirements.

MC:

subcarrier allocation:

each subcarrier is allocated to the user with the best channel gain on that subcarrier.

power allocation:

water-filling algorithm.

optimization formulation:

constraint
$$\begin{cases} P_{k,n} > 0 & \text{(power for subcarrier } n \text{. user } k \text{ should be greater than 0).} \\ \sum_{k=1}^{K} \sum_{n=\Omega_k} P_{k,n} \leq P_t & \text{(total subcarrier power should be} \leq \text{total transmit power)} \\ \Omega_i \cap \Omega_j = \phi \ (i \neq j) & \text{(orthogonal subcarrier set for each user)} \\ \Omega_1 \cup \Omega_2 \cup \ldots \cup \Omega_K \subseteq \{1, 2 \ldots N\} & \text{(subcarrier sets must be available subcarriers).} \end{cases}$$

function

$$\max J = \sum_{k=1}^{K} R_k$$ (capacity = sum of data rate of users)

→ RA doesn't depend on QoS requirements.

PF (fairness coefficients $R_1 : R_2 : \cdots : R_K = \eta_1 : \eta_2 : \cdots : \eta_K$)
tradeoff between capacity and fairness

constraints
$$\begin{cases} P_{k,n} \geq 0 \\ \sum_{k=1}^{K} \sum_{n=\Omega_k} P_{k,n} \leq P_t \\ \Omega_i \cap \Omega_j = \phi \quad (i \neq j) \\ \Omega_1 \cup \Omega_2 \cup \cdots \cup \Omega_K \subset \{1, 2, \cdots N\} \\ R_1 : R_2 : \cdots : R_K = \eta_1 : \eta_2 : \cdots : \eta_K = 1 \text{ (fairness)} \end{cases}$$

Suboptimal subcarrier allocation algorithm:

Power allocation:
assume equal power distribution
$$P_{k,n} = \frac{P_t}{N}.$$

Subcarrier allocation:
1) allocate the best subcarrier n for user $k = 1, 2 \cdots K$.
2) update the data rate of k.
3) if there are unallocated subcarrier, find user with the lowest data rate.
4) assign that user the best subcarrier among the rests.

function:
$$\max J = \sum_{k=1}^{K} R_K$$

MWC: (no limitation of data rate for each user)

constraints
$$
\begin{cases}
P_{k,n} > 0 \\
\sum_{k=1}^{K} \sum_{n \in \Omega_k} P_{k,n} \le P_t \\
\Omega_i \cap \Omega_j = \phi \quad (i \ne j) \\
\Omega_1 \cup \Omega_2 \cup \cdots \cup \Omega_K \subseteq \{1, 2, \cdots N\} \\
R_k T \le Q_k
\end{cases}
$$

(T. Q_k fixed. adjust R_k to ensure the whole slot is used sufficiently)
(allocate slots only when insufficient to send data in one slot.

Suboptimal subcarrier allocation algorithm:

power allocation:
assume equal power distribution ($P_{k,n} = \frac{P_t}{N}$)

Subcarrier allocation:

MMWC:

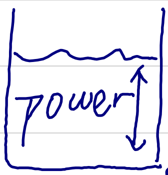
consider the weight not only for each user but also for each subcarrier.
(maximize the summation of weighted data rates for user + subcarrier to increase capacity)

constraints
$$\begin{cases} P_{k,n} \geq 0 \\ \sum_{k=1}^{K} \sum_{n \in \Omega_k} P_{k,n} \leq P_t \\ \Omega_i \cap \Omega_j = \phi \quad (i \neq j) \\ \Omega_1 \cup \Omega_2 \cup \cdots \cup \Omega_K \subseteq \{1, 2 \ldots N\} \end{cases}$$

function

$$\max J = \sum_{k=1}^{K} \sum_{n \in \Omega_K} W_{k,n} R_{k,n}$$

WF algorithm (TX power limited).



← threshold ~ SNR + fading (environment)

← CNR (channel)

constraints

$$\begin{cases} \sum_{k=1}^{K}\sum_{n\in\Omega_k} P_{k,n} = P_t & \text{(total subcarrier power of users equals TX power)} \\ P_{k,n} \geq 0 & \text{(subcarrier power} \geq 0\text{)} \end{cases}$$

function:

Lagrange multiplier

$$J = \sum_{k=1}^{K} R_k + \lambda\left(\sum_{k=1}^{K}\sum_{n\in\Omega_k} P_{k,n} - P_t\right)$$

Optimal solution:

$$P_{k,n} = \begin{cases} \dfrac{P_t + \sum_{i=1}^{K}\sum_{q\in\Omega_i}\frac{1}{r_{i,q}}}{\text{size of}(\Omega_k)} - \dfrac{1}{r_{k,n}} \\ 0 \end{cases}$$

WF: ① SNR > CNR: allocate power to subchannel to ensure $CNR + P_{alloc} = SNR$.

② SNR ≤ CNR: no power allocated to that subchannel.

⇒ fixed SNR.

good channel (CNR ↓)	P_{alloc} ↗
bad channel (CNR ↗)	P_{alloc} ↘

WWF algorithm

constraints
$$\begin{cases} \sum_{k=1}^{K} \sum_{n \in \Omega_k} P_{k,n} = P_t \\ P_{k,n} \geq 0 \end{cases}$$

function:

$$J = \sum_{k=1}^{K} W_k R_k + \lambda \left(\sum_{k=1}^{K} \sum_{n \in \Omega_k} P_{k,n} - P_t \right)$$

optimal solution:

$$P_{k,n} = \begin{cases} \dfrac{W_k}{\sum_{i=1}^{K} (W_i \, \mathrm{sizeof}(\Omega_i))} \left(P_{total} + \sum_{i=1}^{K} \sum_{q \in \Omega_i} \dfrac{1}{r_{i,q}} - \dfrac{1}{r_{k,n}} \right) \\ 0 \end{cases}$$

Scheduling (MAC layer)

algorithms
- minimum bandwidth
  (guarantee the min. b/w for specific service)
- control the delay
  (QoS ⇐ delay)
- maximization of throughput
  (simple. fast. less resource-consumed).

CSI → rate requirements

characteristics of data packets → packet transmission priority

FIFO: scheduling on the arriving order.
pros → simple. fast
cons → no fairness. QoS.

Round-robin: transmit data among different queues in a circle (check all queues before sent).
pros: simplest for allocating the b/w.
cons: inefficiency.

Weighted RR: weight → queue length. packet delay. number of slots to adjust throughputs & delays

Deficit RR: compensates the unselected queues caused by overlength in the next round.

Fair queueing: divides the network capacity into equal fractions, and each of them is consumed by an active queue.

WFQ: allocated capacity $\propto$ weights
(complex. conventional)

Scheduling: determine the received data sending order according to delay, size and QoS.

packet weight
→ optimize the Tx. order
→ reduce the complexity by choosing the number of selected packets for weight calculation.

↳ guarantees system throughput

M-LWDF (suitable for shared wireless link with diff. QoS)
uses the state info of the current channel and queue to optimize the system throughput.

- control flow delays
- provide minimum throughput guarantees

$$W_i = -\frac{S_i \log(\delta_i)}{U_i \bar{R}_i}$$

S_i - HOL packet delay $(T_c - T_p)$

δ_i - maximum probability that the HOL packet delay > delay threshold

U_i - delay threshold / tolerance

$\bar{R}_i$ - avg. queue data length ?

Service nature → U_i, δ_i

delay → S_i

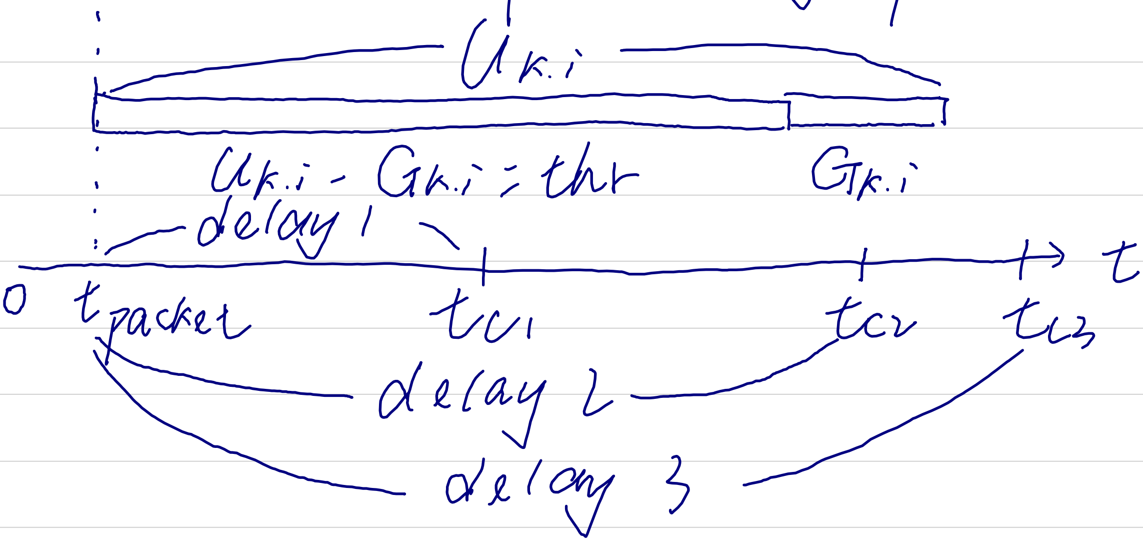
queue length → $\bar{R}_i$?

serve the stream

not guarantee the reliability / delay.

PD: different packet, different weight.

Served packet by packet.



delay 1 $\in [0, thr)$: non-urgent

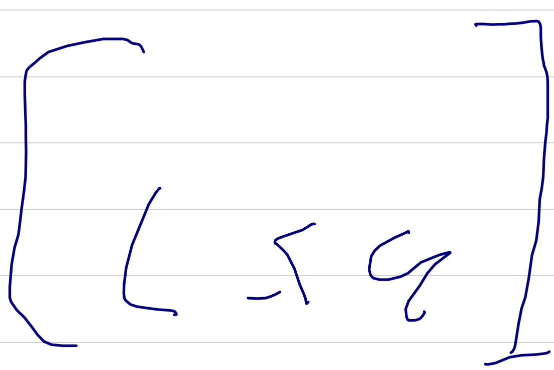
$$W_{k.i.1} = \frac{Q_{k.i} S_{k.i}}{U_{k.i} - G_{k.i} - D_{k.i.1} + 1} = \frac{Q_{k.i} S_{k.i}}{thr - delay + 1}$$

delay 2 $\in [thr, U_{k.i})$

$$W_{k.i.1} = Q_{k.i} S_{k.i}$$

delay 3 $\in [U_{k.i}, +\infty)$

dropped. [G] → drop rate]



I. Introduction

MAC layer: employ weight to determine transmission order.

PHY layer: allocate resource by summing up the weights of the selected packet.

resource allocation:

1. adaptive subcarrier bit and power allocation => minimize the total transmit power (OFDM + fixed R)

2. joint subcarrier and power allocation algorithm => maximize the weighted sum capacity (fixed power + delay)

3. utility function => QoS

4. power allocation of multimedia CDMA cellular network => maximize the weighted sum capacity

PHY layer:

Power ↓ + weighted sum capacity ↗

data scheduling:

1. modified largest weighted delay first => ① larger head-of-line packet delay relative to delay bound. ② high instantaneous data rate ③ higher requirement for the outage probability

2. urgency and efficiency based packet scheduling scheme (OFDM) — utility function of HOL delay + channel capacity.

3. maximum delay utility based cross-layer design [RA + DS] — maximize a utility function of delay

4. genetic algorithm [RA + DS] — maximize the weighted sum capacity

traffic delay (MAC)

MAC layer:

delay + weighted sum capacity

(look for the largest)

traffic queue based (traditional):

packets in selected queues served first.

⇓

inefficiency if urgent in unselected queues.

packet based [11]:

① for GSM/EDGE systems only.
② didn't consider system capacity.
③ didn't consider system with heterogeneous traffic for each user.

adaptive cross-layer design:
→ maximize the weighted sum capacity (downlink + multiuser + multitasking + OFDM)

base: OFDM + heterogeneous traffic queues

DS: packet dependent
→ transmission order ~ assigned packet weight

delay packet size QoS priority

RA: user based, maximize weighted sum capacity. (lower complexity than queue based).

$$W_{user} = \sum W_{\text{selected packets}}$$

choosing the number of selected packets

⇓

reduction of the overall complexity.

△ OFDM

high data rate modulating stream → (simultaneously) slowly modulated narrowband close-spaced carriers

1) less sensitive to selective fading

2) high spectral efficiency

3) adaptive for carrier $\begin{cases}\text{power allocation} \\ \text{modulation scheme}\end{cases}$

↳ Tx + Rx : linear.

II. Model

PHY layer:

subcarrier → subcarrier allocation
power controller → power allocation

MAC layer:

traffic controller → data scheduling

traffic controller
QoS info. ↓ ↑ allocation results
Subcarrier + power controller

△ maximum weighted sum capacity (MWSC)
→ user's instantaneous capacities

III. Resource Allocation

suboptimal algorithm:

performs subcarrier allocation and power allocation separately.

Subcarrier Allocation:

assign subcarrier to user with larger J.

Power Allocation:

KKT conditions

IV. Packet dependent scheduling

1. M-LWDF

$\boxed{\text{keeps the delays of most queues below a bound.}}$

weight (of queue i): $W_i = -\frac{S_i \log(\delta_i)}{U_i R_i}$

U_i - delay tolerance
S_i - HOL packet delay
δ_i - maximum allowed probability that $S_i > U_i$. (system requirement)

HOL (head-of-line)
a performance-limiting phenomenon that occurs when a line of packets is held up by the first packet.

2. MDU

maximises the utility functions with respect to the delay.

average HOL packet delay $\bar{S}_i = \frac{\bar{Q}_i}{\bar{\lambda}_i} = \frac{\bar{Q}_i}{\bar{R}_i}$

$\bar{\lambda}_i$ - avg. arrival rate of queue i

$\bar{Q}_i$ - average queue length

Q_i - the length of queue i in current slot

$\bar{Q}_i'$ - the average length of queue i calculated in previous slot.

$\bar{Q}_i = \alpha Q_i + (1-\alpha)\bar{Q}_i'$. $0<\alpha<1$

$w_i = \frac{-1}{\bar{\lambda}_i} \frac{df_i(\bar{S}_i)}{d\bar{S}_i}$

voice - low
VBR video - medium
BE traffic queues - high

3. PD

Assigns different weights to different packets in the same queue, based on the delay, packet size and QoS.

$U_{k,i}$ - delay tolerance for queue i, user k. (same for packets of same queue)

$G_{k,i}$ - guard interval
[urgent pkts: high priority, last duration]

t_c - current time

t_l - lth packet arriving time

$S_{k,i,l} = t_c - t_l$ (delay)

$C_{k,i,l} = U_{k,i} - S_{k,i,l} - G_{k,i}$ [in msec.]
(time left that the packets become urgent)

if $C_{k,i,l} < 0$, the packet is urgent and with high priority.

$D_{k.i.l}$ - packet l size.

$\beta_{k.i} \in [1, \infty)$ - QoS priority level
(same for queues)

$$W_{k.i.l} = \begin{cases} \dfrac{\beta_{k.i} D_{k.i.l}}{C_{k.i.l} + 1} & (C_{k.i.l} \geq 0) \\ \beta_{k.i} D_{k.i.l} & (C_{k.i.l} < 0) \end{cases}$$

high weight → high QoS priority level ($\beta_{k.i}$)
→ large data ($D_{k.i.l}$)
→ fewer time left to become urgent

packets ← sequence number
(reassembled during transmission)

① $C_{k,i,l} > 0$:

$C_{k,i,l} \downarrow \Rightarrow W_{k,i,l} \nearrow$

$$\frac{\partial W_{k,i,l}}{\partial C_{k,i,l}} = -\frac{\beta_{k,i} D_{k,i,l}}{(C_{k,i,l}+1)^2}$$

larger $C_{k,i,l}$, less sensitivity to $C_{k,i,l}$ change

$\Rightarrow \beta_{k,i}$ & $D_{k,i,l}$ dominate

② $C_{k,i,l} < 0$ (i.e. $U_{k,i} - G_{k,i} < S_{k,i,l}$)

packets should be given a high priority.

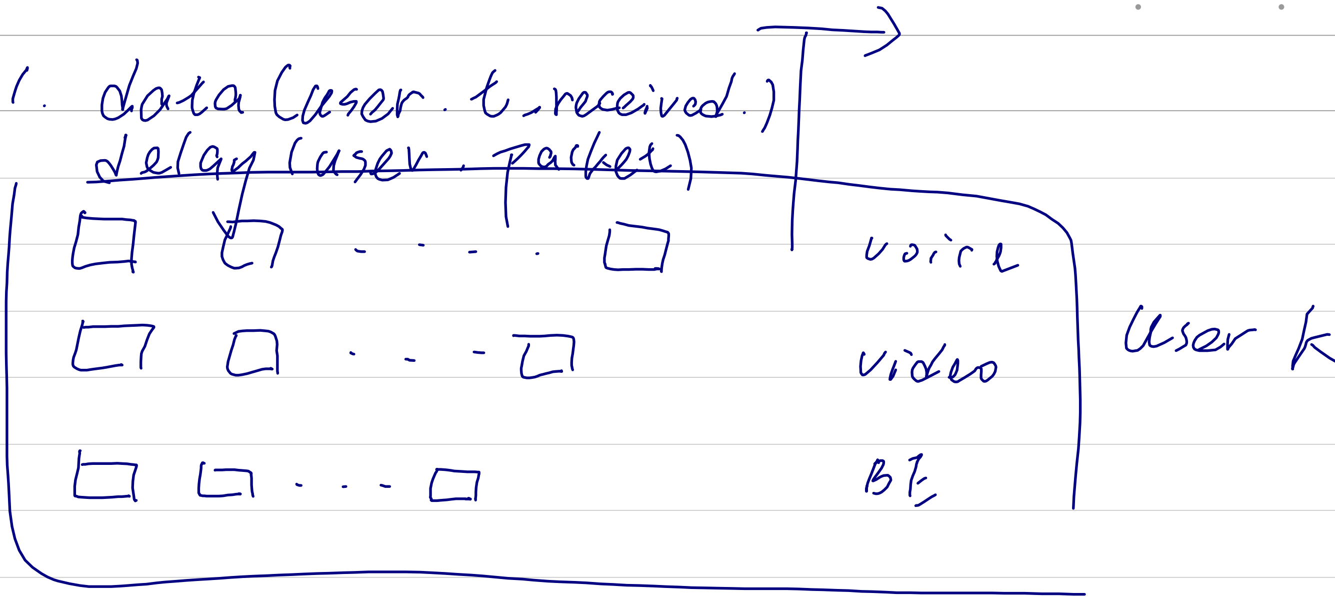
$W_{k,i,l}$ reaches max value ($\propto \beta_{k,i} \cdot D_{k,i,l}$)

- Select only the first $\Lambda_{k.i}$ to-be-served packets (most urgent packets) for weight calculation of MWSC.

$$\Lambda_{k.i} \begin{cases} \nearrow \text{time out within } G_{k.i} & \mathbb{I}^{u}_{k.i} \\ \searrow \text{time out after } G_{k.i} & \overline{\mathbb{I}^{u}_{k.i}} \end{cases}$$

$$W_k = \sum_{i=1}^{I_k} \beta_{k.i} \left[\sum_{l \in \mathbb{I}^{u}_{k.i}} D_{k.i.l} + \sum_{l \in \overline{\mathbb{I}}^{u}_{k.i}} \frac{D_{k.i.l}}{C_{k.i.l}+1} \right]$$

1. data(user, t_received)
delay(user, packet)



$t_c = 1$

$data_1 \cdot R_{k,1}$ $\quad data_1 - 10^{-3} R_{k,1} \le 0 \quad delay_{p_1} = 0$

$t_c = 2$

$\underline{data_2} \cdot R_{k2}$ $\quad \underline{data_2 - 10^{-3}(R_{k_1} + R_{k_2})} \le 0 \quad delay_{p_2} = 0$

$data_1 - 10^{-3}(R_{k_1} + R_{k_2}) \le 0 \quad delay_{p_1} = 1$

$t_c = 3$

$data_3 \cdot R_{k3}$ $\quad data_3 - 10^{-3}(R_{k_1} + R_{k_2} + R_{k_3}) \le 0 \quad delay_{p_3} = 0$

$data_2 - 10^{-3}(R_{k_1} + R_{k_2} + R_{k_3}) \le 0 \quad delay_{p_2} = 1$

$data_1 - 10^{-3}(R_{k_1} + R_{k_2} + R_{k_3}) \le 0 \quad delay_{p_1} = 2$