PHY-MAC Cross-layer: multiuser systems

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6. Energy optimal control for Time Varying wireless networks (multiuser)

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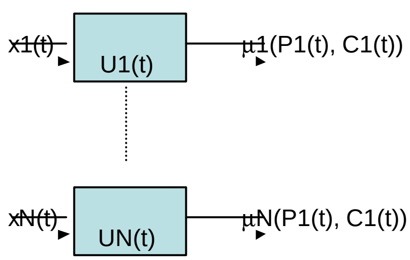
Introduction



P1(t)+…+PN(t)<PT

Problems to be addressed:

- Power and server allocation in multiuser systems: N users but K<N servers
- Which is the power and server allocation policy that stabilizes the system?
- A bound on average delay is established

In other words….

A controller allocates power to each of the N queues at every instant of time
In reaction to channel state information

In order to:

Estabilize the system and achieve maximum throughput and maintain
Acceptable low levels of unfinished work in all the queues

Power and Server allocation

The channel states are

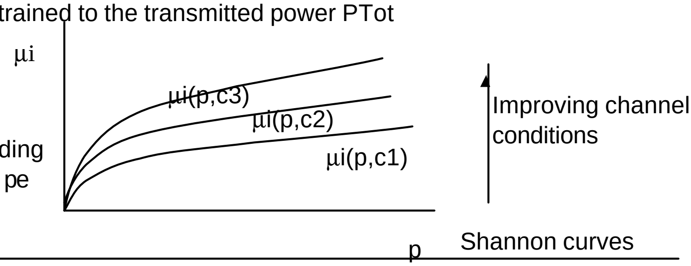
$$C(t) = \left(C_1(t)..C_N(t)\right) \qquad C(t) \in S_1 x S_2 x..x S_N$$

Constant during T, with transitions at t=KT

p_C Are the time average probabilities for each state C

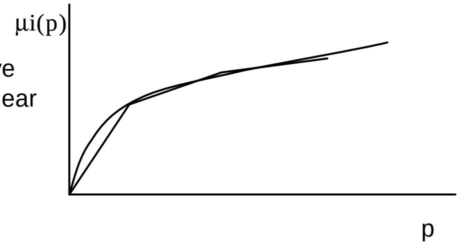
P(t)=(P1(t), …., PN(t)) is the power allocation vector, that controls the server rates and constrained to the transmitted power PTot

Each curve is a
Specific set of coding
Schemes for low pe



- Although in practice: there is only a finite bank of coding schemes

Still concave curve
but piece wise linear



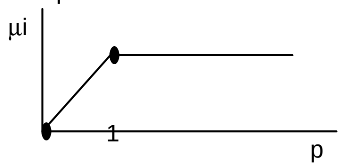
How does the server allocation problem relates to the power allocation problem?

- Every time slot the servers are scheduled to serve K of the N queues
- Queue i tx at μi whenever a server is allocated to it

Transformed into a power allocation problem

$$\sum p_i \le K$$

$$\tilde{m}_i(p) = \begin{cases} m_i p & p \in [0,1] \\ m_i & p > 1 \end{cases}$$



- Example of server allocation algorithm

N=3 K=2
(μ1 μ2 μ3)=(1 1 ½)
L=1 (length of arrival packets)
Bernoulli process (p1 p2 p3)=(p p (1-pp)/2+ε

p<1/2 0<ε<pp/2

Policy: serve the fastest queue (non empty)

-1 and 2 have priority
-3 is served with (1-pp)/2 Unstable because it cannot support its input rate

Stability and downlink capacity region

Stability criterion for 1 queue

X(t): ergodic input process with rate λ

It is the total amount of bits that arrived during [0,T]

μ(t): instantaneous bit processing rate in the server

U(t): unprocessed bits in the queue at time t

$$l = \lim_{t\to\infty} \frac{X(t)}{t} \qquad \underline{m} = \liminf_{t\to\infty} \frac{1}{t}\int_0^t m(t)\,dt$$

$$m(t) \le m_{\max} \quad \forall t \to 0 \le \underline{m} \le m_{\max}$$

$$g(M) = \limsup_{t\to\infty} \frac{1}{t}\int_0^t 1_{[U(t)>M]}\,dt$$

OVERFLOW function

g(M) measures the fraction of time that the unfinished work in a queue is above a certain value M

The network of a single queue is stable if g(M) tends to 0 as M tends to inf.

Then

$$l \le \underline{m}$$

Proof:

$$As \quad l_i \le \underline{m}_i \quad \forall i \in \{1 \ldots N\} (\, for\ all\ queues)$$

$$We\ upperbound\ \underline{m}_i\ as\ follows$$

$|T_{\underline{C}}(t)|$ Total length of intervals when the channel is in state **C**

$|C|$ Total number of states in the system

$$\frac{|T_{\underline{C}}|}{\tilde{t}} \leq p_{\underline{C}} + e \quad \forall \underline{C} \qquad (1)$$

$$\underline{m}_i \leq \frac{1}{\tilde{t}} \int_0^{\tilde{t}} m_i(p_i(t), c_i(t))\, dt + e \quad \forall i \in \{1 \ldots N\}$$

Thus, under power decisions **P**(t) we have for all i

$$l_i \leq \underline{m}_i \leq \sum_{\underline{C}} \frac{|T_{\underline{C}}|}{\tilde{t}} \frac{1}{|T_{\underline{C}}|} \int_{t \in T_{\underline{C}}} m_i(p_i(t), c_i(t))\, dt + e$$

$$\leq \sum_{\underline{C}} \frac{|T_{\underline{C}}|}{\tilde{t}} m_i \left(\frac{1}{|T_{\underline{C}}|} \int_{t \in T_{\underline{C}}} p_i(t)\, dt, c_i(t) \right) + e$$

From concavity of μi

$$\leq \sum_{\underline{C}} (p_{\underline{C}} + e)\, m_i \underbrace{\left(\frac{1}{|T_{\underline{C}}|} \int_{t \in T_{\underline{C}}} p_i(t)\, dt, c_i(t) \right)}_{p_i^{\underline{C}}} + e$$

From (1)

$$l_i \leq \sum_{\underline{C}} p_{\underline{C}} \quad m_i\left(p_i^{\underline{C}}, c_i\right) + e\left(1 + |\underline{C}|\, m_{\max}\right)$$

Thus the capacity region (at network level) is:

$$l_i \leq \sum_{\underline{C}} p_{\underline{C}} \quad m_i\left(p_i^{\underline{C}}, c_i\right) \quad i \in \{1 \ldots N\}$$

Theorem on the stability on the downlink

Definition (from a network theory point of view):

It is the compact set of points such that all queues of the system can be stabilized (with some power allocation policy) whenever the vector of input rates λ=(λ1….λN) is strictly in the interior of the set, and conversely

Theorem of the capacity region at the network level

The capacity region of the downlink channel with PTot and rate power curves μi(pi,ci) (cross-layer) is the set of all input rate vectors λ such that exists pic satisfaying

$$\sum_i p_{ic} \le P_{TOT} \quad \forall C$$

$$l_i \le \sum_C p_c \, m_i(p_{ic}, c_i) \quad i \in \{1 \ldots N\}$$

Stabilizing power allocation algorithm

BUT πc and λi need to be known

Solution to get a stabilizing and feasible power allocation algorithm

In essence, the policy learns the system parameters indirectly by basing power allocation decisions both on channel state and queue backlog information

At the beginning of each slot, observe U(t), C(t) and allocate P(t) such that

$$\sum_i p_i(t) \le P_{Tot}$$

$$\max_P \sum q_i U_i m_i(p_i, c_i)$$

The slowest

The fastest

Corollary: downlink delay bound

$$\sum q_i \overline{U_i} \leq \frac{TB}{2e} \qquad B, e > 0$$

By Little's theorem

$$\sum q_i \, l_i \overline{D_i} \leq \frac{TB}{2e}$$

Comments on implementation

The problem is a non-linear optimization one. But as µi are concave in the power parameters: the problem can be computed efficiently

For

$$m_i\left(p_i, a_i\right) = \log(1 + a_i p_i)$$

The solution is found by

L: set of downlinks i:1…N such that Ui(t)>0

$$p_i = \frac{q_i U_i(t)\left(P_{Tot} + \sum_{j \in \Lambda} \frac{1}{a_i}\right)}{\sum_{j \in \Lambda} q_j U_j(t)} - \frac{1}{a_i} \qquad if \quad i \in \Lambda$$

$$p_i = 0 \quad otherwise$$

Process ending at most in N-1 iterations

Proof of the stability

For stability analysis, the following Lyapunov function is defined

$$L(\underline{U}) = \sum_i q_i U_i^2$$

Sufficient conditions for the system to be stable and have well-defined steady state distribution of unfinished work U

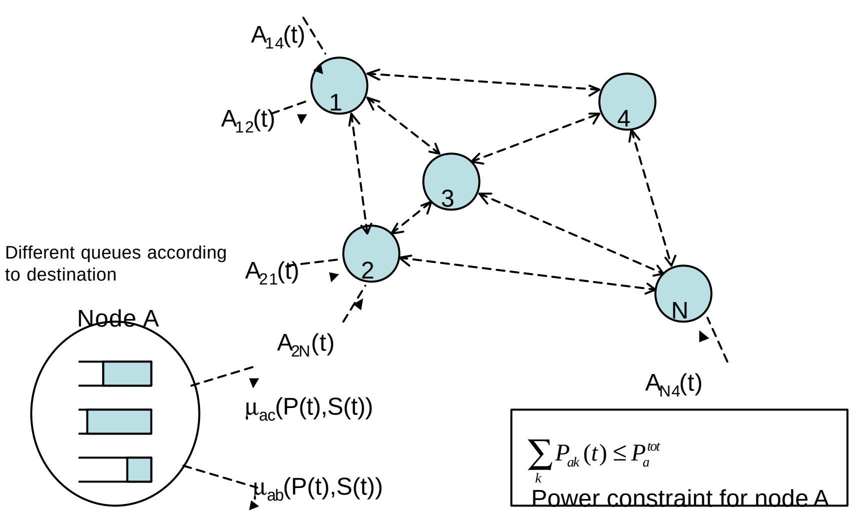
1) $E\left[L(U(t+T))/U(t)\right] < \infty \quad \forall U \in R^N$

2) $E\left[L(U(t+T)) - L(U(t))/U(t)\right] < -\infty \quad if\ U(t) \notin \Lambda$

3) $If \quad U(t) \in \Lambda \quad p\{U(t+mT) = 0\} \neq 0$

Then a steady state distribution on vector U exists and hence the system is stable

Dynamic power allocation and routing



Assumptions

- Power constrained nodes
- Time is slotted, channel changes from slot to slot
- Variable transmission rates $\mu(P,S)$
- Cell partitioned network model

S(t): Channel matrix process
Ergodic with time average probabilities π_s for each state **s**

P(t): power metric $\in \Pi$, where Π is a compact set of acceptable power Allocations that includes the power limits for each node

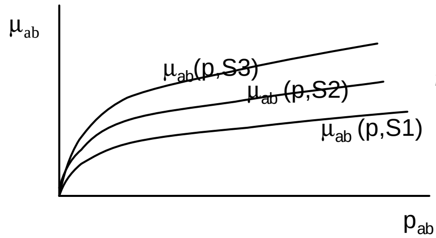
GOAL:
- Stabilize the system and thereby achieve maximum throughput and mantain acceptably low network delay: by means of joint routing and power allocation policy.
- This work unifies : network capacity, network optimization, network control

New concept: Network capacity region. It is a network layer notion. This is distinct from the information theoretic capacity

-Network capacity region:
- Set of all λ_{ij}
- Considering all possible routing and power allocation strategies
- Depends on: node power constraints, rate-power function

μ (P(t),S(t))

-Information theoretic:
-Optimization over all possible modulation and coding schemes
-Involves many of the unsolved problems of network information theory



$$m_{ab}(P,S) = \log\left(1+\frac{a_{ab}\,P_{ab}}{N_o + a_{ab}\sum_{j\neq b} P_{aj} + a_{ib}\sum_{i\neq a} P_{aj}\sum_{j} P_{ij}}\right)$$

Such curves depend on the SIR at The rx also!!!

The network controller makes the following decisions:

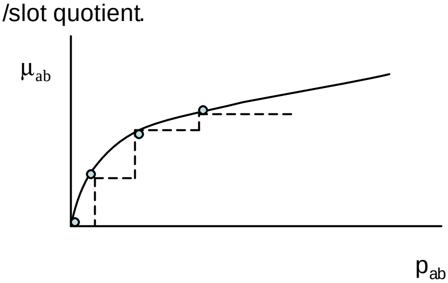
- Power allocation: choose P(t) such that $P(t)\in\Pi$
- Routing/Scheduling: choose $m_{ab}^{(c)}(t)$ such that

$$\sum_{c} m_{ab}^{c}(t) \le m_{ab}(t) = m_{ab}(P(t), S(t))$$

Note that: if no power allocation, $m_{ab}(t)$ is purely determined by the dynamic channel states of the network, and any network control algorithm reduces to pure routing and scheduling

The rate of node a will be controlled with the power as the curves indicate if variable length packets can be split and repackaged with new headers for resequencing at the destination (in the analysis extra bits due to such headers will be neglected)

However, splitting and relabeling can be avoided altogether if all packets have fixed lengths and the transmission rates are restricted to integral multiples of the packet length/slot quotient.



Stability and network capacity region

The goal of the controller is to mantain low backlog and thereby stabilize the System. For that purpose, we take into account the following queueing dynamics

$$U_i^{(c)}(t+1) \le \max\left[U_i(t) - \sum_b m_{ib}^{(c)}(t),\quad 0\right] + \sum_a m_{ai}^{(c)}(t) + A_i^{(c)}(t)$$

A. Stability of queuing systems

Overflow function: $g(V) = \limsup_{t\to\infty} \frac{1}{t}\sum_{t=0}^{t-1} \Pr\left[U(t) > V\right]$

$0 \le g(v) \le 1$

A single server queuing system is stable if $g(V) \to 0 \; as \; V \to \infty$

A network of queues is stable if all individual queues are stable

B. Network capacity

Let's define the input rate as $\lim_{t\to\infty} \frac{1}{t}\sum_{t=0}^{t-1} A_i^{(c)}(t) = l_{ic}$

Theorem 1:

It is the closure of the set of all rate matrices (λ_{ic}) that can be stably supported over the network, considering all possible algorithms. If the flow with destination (c) that enters in node (a) towards (b) is $f_{ab}^{(c)}$

$$f_{ab}^{(c)} \ge 0 \qquad f_{aa}^{(c)} = f_{ab}^{(a)} = 0 \qquad \forall a,b,c$$

$$l_{ic} \le \sum_b f_{ib}^{(c)} - \sum_a f_{ai}^{(c)} \qquad \forall i,c \quad i \ne c$$

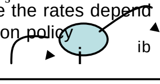
$$\sum_c f_{ab}^{(c)} \le R_{ab} \qquad \forall a,b \quad R_{ab} \in \Gamma$$

This constraint ensures that the total flow over any link does not exceed the link capacity

$$\Gamma = \sum_s p_s \quad convex \quad Hull\left\{m(P,S) \,\middle|\, P \in \Gamma\right\}$$

Graph family because the rates depend On the power allocation policy

Compact set of acceptable power allocations that includes the power limits for each node



Lyapunov theory can be used to design stabilizing power allocation and routing algorithms that do not require knowledge of arrival rates or channel statistics in cases where there are only peak power constraints on the wireless devices.

The proof of theorem 1 involves showing that $l_{ic} \in \Lambda$ is necessary for stability and that l_{ic} interior to Λ is sufficient.

Centralized systems: dynamic control policy

Generalizes Tassiulas-Ephremides by considering:

- Power allocation
- Networks with general interference
- Time-varying channel

Policy:

1) For all links (a,b) find commodity $c^*_{ab}(t)$ such that

$$c^*_{ab}(t) = \arg \max_{C \in \{1 \ldots N\}} \left\{ U_a^{(c)}(t) - U_b^{(c)}(t) \right\}$$

and define

$$w^*_{ab}(t) = \arg \max_{C \in \{1 \ldots N\}} \left\{ U_a^{(c^*_{ab})}(t) - U_b^{(c^*_{ab})}(t), 0 \right\}$$

Maximum differential backlog between a and b

2) Power allocation: choose matrix P(t) such that

$$P(t) = \operatorname{argmax}_{P \in \Pi} \sum_{a,b} m_{a,b}(P, S)\, w^*_{ab}(t)$$

3) Routing: define transmission rates as follows

$$m_{ab}^{(c)}(t) = \begin{cases} m_{ab}(P(t), S(t)) & c = c_{ab}^{*}(t) \quad w_{ab}^{*}(t) > 0 \\ 0 & otherwise \end{cases}$$

Equalize the differential backlog
It can be proved its stability and that the average bit delay satisfies

$$\overline{D}_{bit} = \left(\frac{1}{N\,l}\right)\sum_{i,c}\overline{U_i^{(c)}}$$

$$\overline{D}_{bit} \leq \frac{KBN + (K-1)B'N}{e\,N\,l} = \frac{KBN + (K-1)B'N}{r(1-r)R^2}$$

Distributed implementation

Users attempt now to maximize the weighted sum of data rates in

$$P(t) = \arg\max_{P\in\Pi} \sum_{a,b} m_{a,b}(P,S) \quad w_{ab}^{*}(t) \qquad (*)$$

By exchanging information with their neighbors via a low bandwidth control Channel

We define neighbour set $\Omega_i(t)$ according to best channel conditions

A. Networks with independent channels

Obtained via orthogonal coding schemes , beamforming or channels are Separated such that interference is negligible

The weighted sum in (*) is maximized by separately maximizing each term
Nodes making independent power control and routing decisions based only on their local information

$$\max \sum_{b} w_{nb}^{*}(t)\, m_{nb}(P_{nb}, S_{nb})$$

$$s.t. \quad \sum_{b \in \Omega_n} P_{nb} \le P_n^{Tot}$$

Which can be solved in real-time

B. Networks with interference

There is an initial interference sensing stage. The idea of randomly choosing users to tx. Is similar to the technique used in the Grossglauer-Tse realy algorithm but now, rather that tx. To the nearest rx., the algorithm chooses the rx with the largest backlog-rate arithmetic.

Dynamic optimization contributes to bridging the gap between theoretical optimization techniques and implementation control algorithms.

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