Optimal Resource Allocation for Cellular Networks with MATLAB Instructions

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Chapter 1

Introduction

This report presents a more detailed description of the algorithm and simulations published in papers [1,2]. It includes a step by step description of the algorithm and included the corresponding flow chart. In addition, detailed instructions of the MATLAB code used to simulate the proposed allocation algorithm in [1,2] is presented. The report starts with a brief motivation of resource allocation problem in wireless networks. Then, some of the prior related work on the subject are mentioned. Finally, we provide the details instructions on MATLAB functions used in our algorithm. More rigorous analysis and proofs of the problem and algorithm are present in [1,2] and further discussions presented in [3,4].

1.1 Motivation and Background

There is a significant increase in the number of users and volume of traffic for wireless services [5–8]. Hence, it urges for improvement of quality of experience (QoE) [9], sometimes called quality of service (QoS) in some articles [10–12], of cellular networks [13]. This improvement needs to be conducted on multiple layers of the network. Some progress to enhance the service in link layer has been conducted in [14–17]. Other researchers advanced the user experience by conducting design improvement to physical layer as shown in [18,19]. The utilization of game theory methods in [20,21] and microeconomics in [22,23] provided improvement to QoE.

Relaying on network layer QoS research was conducted by [24] with consideration to energy efficiency. QoS was studied within the context of LTE third generation partnership project (3GPP) standardization [25,27] in [28,29] and within WiMAX [30] in [31,32]. QoS at the Network layer was exploited from
policy management perspective in [33] for Mobile Broadband [34] and in [35] for Universal Mobile Terrestrial System (UMTS) [36, 37]. End to end QoS was proposed in [38] and component-based QoS was proposed in [39]. Another method for improving QoS is via hardware by increasing the battery life which was discussed in [40, 41]. A solution that supports real-time traffic is proposed in [42].

For operators to deliver better service to their customers, QoS needs to be address efficiently via cross-layer design. Some researchers suggested global coordination between layers of Open Systems Interconnection (OSI) model [43] as in [44, 45]. Other researchers modified the Asynchronous Transfer Mode (ATM) network protocol stack to achieve cross-layer QoS as in [46, 47]. One the other hand, application layer QoS was the focus of the study in [48, 49].

For wired IP networks, Integrated Services (IntServ) and Differentiated Services (DiffServ) were proposed in [50, 51] and [52–54], respectively. These methods focus on QoS on the routers in the form of scheduling, routing and shaping.

In dealing with resource allocation various formulations are adapted, e.g. proportional fairness [55–57] and max-min fairness [58–61], as they achieve optimality for inelastic traffic [21, 62]. Network proportional fairness models were proposed with optimal solution for elastic traffic in [63, 64] and weighted fair queuing (WFQ) in [65, 66]. Some attempts to extend to inelastic traffic was conducted in [67]. However, optimality was shown in [68, 69] using convex optimization techniques [70] and the sensitivity to traffic is shown in [71]. Multi-class service offering with real-time application, using sigmoid functions was shown in [72–74]. Extension to include resource blocks were developed in [75–77].

The President’s Council of Advisers on Science and Technology (PCAST)s report [78] recommends the use of the government-held spectrum to expand the available spectrum for mobile communications and so increase the service quality and meet future demands as well [79]. As a result, Federal Communications Commission (FCC) is studying sharing of under-utilized spectrum, e.g. S-band radars [80, 81], with over-utilized spectrum [82, 83] and the National Telecommunications and Information Administration (NTIA) is studying the
effect of interference between mobile broadband systems and other wireless systems, e.g. WiMAX and radar \cite{84,86}.

A non-convex optimization approaches to maximize system utilities for the case of multiple carriers were proposed in \cite{87,91} followed by convex optimization approaches in \cite{92,93}. The aggregation of radar spectrum to cellular spectrum was presented in \cite{94,96} to provide solutions for the spectrum sharing problem presented in \cite{97,100}.

The resource allocation solution proposed in \cite{1,2} is generic and can be applied to many systems, e.g. multi-cast network \cite{101}, ad-hoc network \cite{46,102} and WiFi network \cite{103,105}. Some successful usages of that solution for machine to machine (M2M) communications were conducted in \cite{106,110} where optimization is with latency constraints rather than bandwidth constraints.
Chapter 2

User Applications Utilities

The user satisfaction with the provided service can be expressed using utility functions that represent the degree of satisfaction of the user function of the rate allocated by the cellular network [1,2]. We assume that the applications utility functions \( U(r) \) are strictly concave or sigmoid functions.

2.1 Sigmoid Utility

The normalized sigmoid utility function is used in this cellular system, as in [73,111]. It can be expressed as

\[
U(r) = c \left( \frac{1}{1 + e^{-a(r-b)}} - d \right)
\]  

(2.1)

where \( c = \frac{1+e^{ab}}{e^{ab}} \) and \( d = \frac{1}{1+e^{ab}} \). So, it satisfies \( U(0) = 0 \) and \( U(\infty) = 1 \). The inflection point of normalized sigmoid function is at \( r_{\text{inf}} = b \).

In MATLAB, the sigmoid utility code is

```matlab
y(i) = c(i).*((1./(1+exp(-a(i).*(x-b(i)))))-d(i));
```

where

```matlab
c = (1+exp(a.*b))./(exp(a.*b));
d = 1./(1+exp(a.*b));
```
2.2 Logarithmic Utility

The normalized logarithmic utility function is used as well, as in [57][112][113], that can be expressed as

\[ U(r) = \frac{\log(1 + kr)}{\log(1 + k r_{\text{max}})} \] (2.2)

where \( r_{\text{max}} \) is the rate achieving 100% user satisfaction and \( k \) is the rate of increase with rate \( r \). So, it satisfies \( U(0) = 0 \) and \( U(r_{\text{max}}) = 1 \). The inflection point of normalized logarithmic function is at \( r_{\text{inf}} = 0 \).

In MATLAB, the logarithmic utility code is

```matlab
y2(i) = log(k(i).*x+1)./(log(k(i).*100+1));
```

The utility functions with the parameters in Table 2.1 are shown in Figure 2.1 [1][114].

Table 2.1: Applications Utilities

| Sig1 | \( a = 5, \ b = 10 \) | e.g. VoIP | Log1 | \( k = 15, \ r_{\text{max}} = 100 \) |
|------|----------------------|-----------|------|-----------------------------------|
| Sig2 | \( a = 3, \ b = 20 \) | e.g. SD video streaming | Log2 | \( k = 3, \ r_{\text{max}} = 100 \) |
| Sig3 | \( a = 1, \ b = 30 \) | e.g. HD video streaming | Log3 | \( k = 0.5, \ r_{\text{max}} = 100 \) |

2.3 Utilities used in Simulation

We use three normalized sigmoid function that are expressed by equation (2.1) with different parameters:

- \( a = 5, \ b = 10 \) which is an approximation to a step function at rate \( r = 10 \) (e.g. VoIP),
- \( a = 3, \ b = 20 \) which is an approximation of an adaptive real-time application with inflection point at rate \( r = 20 \) (e.g. standard definition video streaming)
Figure 2.1: Applications Utilities

- $a = 1$, $b = 30$ which is also an approximation of an adaptive real-time application with inflection point at rate $r = 30$ (e.g. high definition video streaming).

We use three logarithmic functions that are expressed by equation (2.2) with $r_{\text{max}} = 100$ and different $k_i$ parameters which are approximations for delay tolerant applications (e.g. FTP). We use $k = \{15, 3, 0.5\}$.

In MATLAB, the code for plotting the utilities and their derivatives code is

```matlab
function utility_fn
close all
clear all
clc
syms x
%x = 0:0.1:100;
k = [15 3 0.5];
a = [5 3 1];
b = [10 20 30];
c = (1+exp(a.*b))./(exp(a.*b));
```
d = 1./(1+exp(a.*b));

for i = 1: length(a)
    y(i) = c(i).*((1./(1+exp(-a(i).*x-b(i))))-d(i));
    y2(i) = a(i).*log(b(i).*x+1)/(1+ a(i).*log(b(i) .*100+1));
    y2(i) = log(k(i).*x+1)./(log(k(i).*100+1));
end

z = log(y);
z2 = log(y2);

for i = 3: 4
    for j = 1: 101
        x0(j) = 0.1 * j;
        yy(j,i) = subs(y(i),x0(j));
        yy2(j,i) = subs(y2(i),x0(j));
        dy(j,i) = diff(y(i),x);
        dy2(j,i) = diff(y2(i),x);
        dyy(j,i) = subs(dy(j,i),x,x0(j));
        dyy2(j,i) = subs(dy2(j,i),x,x0(j));
        ddy(j,i) = diff(dy(j,i),x);
        ddy2(j,i) = diff(dy2(j,i),x);
        ddyy(j,i) = subs(ddy(j,i),x,x0(j));
        ddyy2(j,i) = subs(ddy2(j,i),x,x0(j));
        zz(j,i) = subs(z(i),x0(j));
        zz2(j,i) = subs(z2(i),x0(j));
        dz(j,i) = diff(z(i),x);
        dz2(j,i) = diff(z2(i),x);
        dzz(j,i) = subs(dz(j,i),x,x0(j));
        dzz2(j,i) = subs(dz2(j,i),x,x0(j));
    end
end

subplot(3,1,3); plot(x0,yy,x0,yy2)
subplot(3,1,2);
2.4 Implementation Example

In this example we use utility functions for youtube and FTP file transfer. Empirically, it was found that below 200 kbps, youtube crashed and buffered constantly [115]. Above 740 kbps there was negligible gain. So for your example, a rough estimate would be to use a sigmoid-like utility where

- 200 kbps == 5% satisfaction (or could be something between 1-10%).
- 740 kbps == 99% satisfaction.

with inflection point \( \frac{(740+200)}{2} = 470 \) kbps (i.e. \( b = 470 \) kbps) and the slope is \( \frac{(99-5)}{(740-200)} = 0.174 \) %per kbps (i.e. \( a = 0.174 \)).
Chapter 3

Single Carrier with Single Utility per User

3.1 Optimal Resource Allocation

3.1.1 System Model of Single Carrier with Single Utility per User

In our simulation, we consider a single cell in a mobile network consisting of a single base station and M users (M = 6 shown in Figure 3.1). The bandwidth allocated by the base station to the ith user is given by $r_i$. Each user has its own utility function $U_i(r_i)$ that corresponds to the type of traffic being handled by the user. Our objective in this report, stated more rigorously in [1, 2], is to determine the bandwidth the base station should allocate to the users. We assume the utility functions $U_i(r_i)$ to be strictly concave or sigmoid functions.
3.1.2 Algorithm of Optimal Resource Allocation

Figure 3.2: Base Station Algorithm of Single Carrier with Single Utility per User

The distributed resource allocation algorithm for a single carrier cell with users with single utility. It is an iterative solution for allocating the network resources with utility proportional fairness. The algorithm is divided into an user algorithm shown in flow chart in Figure 3.3 and a base station algorithm shown in flow chart in Figure 3.2. Flow Chart Description:

- Each user starts with an initial bid $w_i(1)$ which is transmitted to the base station.
In MATLAB
1. \% Initial Bids
2. \texttt{w = [10 10 10 10 10 10];}

- The base station calculates the difference between the received bid $w_i(n)$ and the previously received bid $w_i(n-1)$ and exits if it is less than a pre-specified threshold $\delta$.

In MATLAB
1. \texttt{while (delta > 0.001) \% (time<80) \{

Figure 3.3: User Algorithm of Single Carrier with Single Utility per User
• We set $w_i(0) = 0$. If the value is greater than the threshold $\delta$, base station calculates the shadow price $p(n) = \frac{\sum_{i=1}^{M} w_i(n)}{R}$ and sends that value to all the users.

In MATLAB

```matlab
function [p] = base station(w,Rate)
R = Rate;
p = sum(w)/R;
```

• Each user receives the shadow price to solve for the rate $r_i$ that maximizes $\log U_i(r_i) - p(n)r_i$.

In MATLAB

```matlab
for i = 1: length(a)
    y(i) = log(c(i).* (1./ (1+exp(-a(i).* (x-b(i)))))) - d (i));
    y(length(a)+i) = log(log(k(i).* x+1))./ (1+ log(k( i).*100+1)));
end
for i = 1: 2*length(a)
    dy(i) = diff(y(i),x);
end
S(i) = dy(i)-p(time);
soln(i,:) = double(solve(S(i)));
```
• That rate is used to calculate the new bid \( w_i(n) = p(n)r_i(n) \).

In MATLAB
\[
1 \quad w(i) = r_{opt}(i) \times p(time);
\]

• Each user sends the value of its new bid \( w_i(n) \) to the base station. This process is repeated until \(|w_i(n) - w_i(n-1)|\) is less than the pre-specified threshold \( \delta \).

In MATLAB
\[
1 \quad \text{while} \quad (\text{delta} > 0.001) \quad \%(\text{time}<80)\%
2 \quad : \quad \%
3 \quad : \quad \%
4 \quad : \quad \%
5 \quad : \quad \\
6 \quad \text{delta} = \text{max}(\text{abs}(w-w_{old}))
7 \quad \text{end}
\]

The implementation of optimization problem using non-linear equation solution:
• The solution \( r_i \) of the optimization problem \( r_i(n) = \arg \max_{r_i} \left( \log U_i(r_i) - p(n)r_i \right) \) in flow chart in Figure 3.3 is the value of \( r_i \) that solves equation \( \frac{\partial \log U_i(r_i)}{\partial r_i} = p(n) \).

In MATLAB:
\[
1 \quad \text{dy}_\text{sig}(i) = a(i).*m(i)./((1+m(i)).*(1-d(i).*((1+m(i)))));
2 \quad \text{dy}_\text{log}(i) = k(i)./((1+k(i).*x).*log(1+k(i).*x));
\]

• It is the intersection of the horizontal line \( y = p(n) \) with the curve \( y = \frac{\partial \log U_i(r_i)}{\partial r_i} \) which is calculated in the \( i^{th} \) user.

In MATLAB:
\[
1 \quad \text{soln}(i) = \text{fzero}(@(x) \text{utility}_\text{UE}(x,ii,pp),[.001 1000])
\]
3.2 Robust Optimal Resource Allocation

In this section, we present our robust algorithm to ensure the rate allocation algorithms in the flow chart in Figure 3.3 converges for all values of the base station total rate $R$.

3.2.1 System Model of Robust Resource Allocation

Similar to Section 3.1.1.

3.2.2 Fluctuation Decay Function

In this section, we show our robust algorithm to ensure the rate allocation algorithms in flow chart Figure 3.3 converges for all values of the base station total rate $R$. Our algorithm allocate rates coincide with the Algorithm in flow...
chart in Figure 3.3 and in Figure 3.2 for $\sum_{i=1}^{M} b_i > R$. For $\sum_{i=1}^{M} b_i \ll R$, our algorithm avoids the fluctuation in the non-convergent region discussed in the previous section. This is achieved by:

- adding a convergence measure $\Delta w(n)$ that senses the fluctuation in the bids $w_i$.
- In case of fluctuation, our algorithm decreases the step size between the current and the previous bid $w_i(n) - w_i(n-1)$ for every user $i$ using fluctuation decay function.

The fluctuation decay function could be in the following forms:

- **Exponential function**: It takes the form $\Delta w(n) = l_1 e^{-\frac{n}{l_2}}$.
- **Rational function**: It takes the form $\Delta w(n) = \frac{l_3}{n}$.

where $l_1, l_2, l_3$ can be adjusted to change the rate of decay of the bids $w_i$.

The new addition in MATLAB with the fluctuation decay function is

```matlab
if abs(w_old(i)-w(i)) > (5.*exp(-0.1*time))%(10./time)
  w(i) = w_old(i) + (5.*exp(-0.1*time)) .* sign(w(i)-w_old(i));
end
```

**Remark 3.2.1.** The fluctuation decay function can be included in user Algorithm or base station Algorithm.

### 3.2.3 Algorithm of Robust Optimal Resource Allocation

The algorithm is divided into an user algorithm shown in Figure 3.6 and an base station algorithm shown in Figure 3.5.

**Flow Chart Description:**

- Each user starts with an initial bid $w_i(1)$ which is transmitted to the associated base station.

In MATLAB
% Initial Bids
w = [10 10 10 10 10 10];

• The base station evaluates the difference between the received bid $w_i(n)$ and the previously received bid $w_i(n-1)$ and exits if it is less than a threshold $\delta$.

In MATLAB

while (delta > 0.001) \%(time<80)\%( 
  : 
  : 

Figure 3.5: Robust Base Station Algorithm
delta = max(abs(w-w_old))

- Lets set \( w_i(0) = 0 \). If the value is greater than the threshold \( \delta \), base station calculates the shadow price \( p(n) = \frac{\sum_{i=1}^{M} w_i(n)}{R} \) and sends that value to all the users.

In MATLAB

```matlab
function [p] = base station(w,Rate)
R = Rate;
p = sum(w)/R;
```

- Each user receives the shadow price to solve for the rate \( r_i \) that maximizes \( \log U_i(r_i) - p(n)r_i \).

In MATLAB

```matlab
for i = 1: length(a)
y(i) = log(c(i).*((1./(1+exp(-a(i).*x-b(i)))))−d(i));
y(length(a)+i) = log(log(k(i).*x+1)./(1+ log(k(i).*100+1)));
end
for i = 1: 2*length(a)
dy(i) = diff(y(i),x);
end
S(i) = dy(i)-p(time);
soln(i,:) = double(solve(S(i)));
```

- That rate is used to calculate the new bid \( w_i(n) = p(n)r_i(n) \).

In MATLAB
\[ w(i) = r_{\text{opt}}(i) \ast p(time); \]

- If the step size between the current and the previous bid \(|w_i(n) - w_i(n - 1)|\) for every user \(i\) is greater than \(\Delta w(n)\) then use the fluctuation decay function.

In MATLAB:
```matlab
if abs(w_old(i) - w(i)) > (5.*exp(-0.1*time))
    w(i) = w_old(i) + (5.*exp(-0.1*time)) \ast sign(w(i) - w_old(i));
end
```

- Each user sends its new bid \(w_i(n)\) to the base station. This process is repeated until \(|w_i(n) - w_i(n - 1)|\) is less than the threshold \(\delta\).

In MATLAB:
```matlab
while (delta > 0.001) \% (time<80)\%
    :
    :
    :
    :
    delta = max(abs(w-w_old))
end
```
Figure 3.6: Robust User Algorithm

1. Send initial bid $w_j(l)$
2. Receive shadow price $p(n)$
3. Solve $r_j(n) = \arg \max (\log U_i(r_j)) - p(n)r_j$
4. If $|w^u_j(n) - w^u_j(n-1)| > \Delta w(n)$, then:
   - $w^u_j(n) = w^u_j(n-1) + \text{sgn}(w^u_j(n) - w^u_j(n-1))\Delta w(n)$
5. If $r_j(n)$ is allocated, send new bid $w_j(n) = p(n)r_j(n)$
6. Otherwise, stop.
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