# Application-Aware Resource Allocation with Carrier Aggregation using MATLAB

**by**

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# Chapter 1

# Introduction

This is a guide for plotting the figures in the published paper [2]. We start by providing motivation and background on resource allocation problem followed by literature review of related work. We describe the utilities used for the carrier aggregation problem under discussion. Finally, a step by step MATLAB guide for implementing the algorithm in [2] is presented. For more details on our carrier aggregation work, please check [2–6].

## 1.1 Motivation, Background, and Related Work

One of the important aspects of mobile communications is quality of service (QoS) [7–9] or refereed to as quality of experience (QoE) [10, 11] for end user experience. Due to the significant increase in mobile traffic in recent years [12–15], more attention to QoE, a.k.a. QoS,is on the rise. Therefore we can find QoS research conducted on different layer and with various methods. For example, network layer QoS was conducted by [16–19] while physical layer QoS was conducted by [20, 21], game theory methods used in [22, 23], and microeconomics utilization used in [24, 25].

Researchers conducted studies and provided various QoS improvements for different wireless standards. For instance, QoS of network layer with energy efficiency was studies in [26–28] for LTE third generation partnership project (3GPP) [29–31]. Similarly, QoS improvements were conducted in [32, 33] for WiMAX [34], in [35] for Universal Mobile Terrestrial System (UMTS) [36, 37], and in [38] for Mobile Broadband [39]. Application layer QoS was the focus of the studies in [40, 41].

For more improvement in the service quality, some researchers studies cross-layer design of Open Systems Interconnection (OSI) model [42] for QoS improvement [43,44]. Hence, QoS in the form of shaping and scheduling of routers was studied in [45, 46] and [47–49] for Integrated and Differentiated Services, respectively, and Asynchronous Transfer Mode (ATM) was studied in [50, 51]. A focus on battery life and embedded-based QoS improvement were also of interest to researchers in [52–56].

Various problem formulations for resource allocation optimization problem has been conducted for elastic traffic [23,57], e.g. proportional fairness [58–60], and max-min fairness [61–64]. Popular optimal solution of the problem for elastic traffic was presented in [65, 66] for proportional fair case and in [67, 68] for weighted fair queuing case. An approximate solution for the problem in case of inelastic traffic was presented in [69] and a multi-class service offering was shown in [70, 71]. The optimal solution of the problem for inelastic traffic was shown in [72, 73] using convex optimization [74]. A follow-up extension of the problem to include multiple applications per user was shown in [75–78].

Another important aspect of the problem is carrier aggregation along with resource allocation [5, 6]. Given the President Council of Advisers on Science and Technology report [79], carrier aggregation between heterogeneous spectra is the future of resource allocation [3, 4, 80]. Hence, the Federal Communications Commission (FCC) suggested the use of radar band [81, 82] with cellular band [83, 84], and the National Telecommunications and Information Administration (NTIA) provided useful studies on the interference effects of radar/comm coexistence [85–87].

Some researchers introduced carrier aggregation scenarios using non-convex optimization methods in [88–92], while other researchers presented convex optimization formulation of the problem in [2, 93]. Further inclusion of radar band in particular as a secondary band was provided in [94–96] for the radar/-comm coexistence problem [97–100].

Other problems of interest that can benefit from the simulation tools provided in this guide are machine to machine communications (M2M) in [101–103], multi-cast network [104], ad-hoc network [105–108], and other wireless networks [109–112].

## 1.2 User Applications Utilities

In our simulation, a utility function is a representation of the corresponding user satisfaction with the provided service. We assume that two types of applications can run on user's smart phone, either real-time application with a sigmoid utility function [71, 113, 114] or a delay-tolerant application with a logarithmic utility function [60, 115, 116]. The mathematical representation of the real-time application is as follows

$$U(r) = c\Big(\frac{1}{1+e^{-a(r-b)}} - d\Big) \tag{1.1}$$

where $c = \frac{1+e^{ab}}{e^{ab}}$ and $d = \frac{1}{1+e^{ab}}$ with MATLAB code [1]

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

while the mathematical representation of the delay-tolerant application is as follows

$$U(r) = \frac{\log(1+kr)}{\log(1+kr^{\max})} \tag{1.2}$$

where $r^{\max}$ and $k$ are 100% user satisfaction rate and rate increase, respectively, with MATLAB code [1]

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

In [2], the parameters in Table 1.1 are used and shown in Figure 1.1 [117–119].

Table 1.1: Applications Utilities [1]

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

Realistic values of $a$, $b$ and $k$ for real mobile applications, e.g. youtube and FTP, are shown in [1, 120, 121].

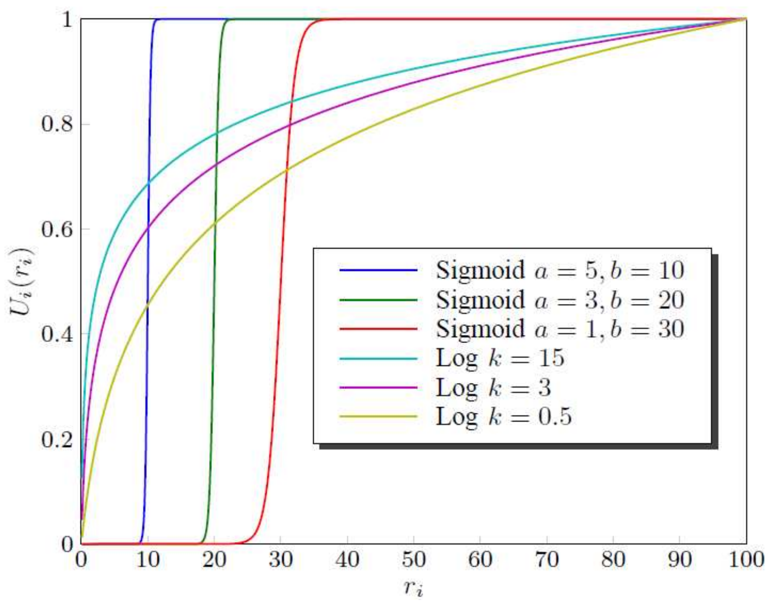


Figure 1.1: Applications Utilities [1]

# Chapter 2

# Carrier Aggregation

## 2.1 System Model of Joint Carrier Aggregation

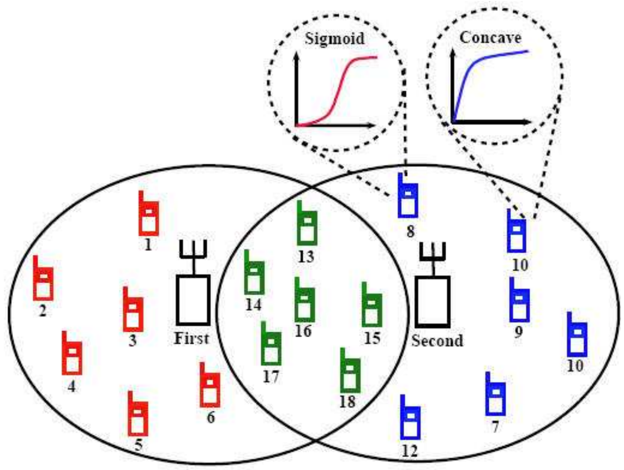


Figure 2.1: System Model of Joint Carrier Aggregation

A mobile system [2] consisting of $K = 2$ carriers in $K = 2$ cells is considered. User equipments (UE)s are distributed in these cells, we consider $M = 18$ UEs in this simulation, as shown in Figure 2.1. A rate $r_{li}$ from the $l^{th}$ carrier to $i^{th}$ UE is allocated where $l = \{1, 2, ..., K\}$ and $i = \{1, 2, ..., M\}$. Each user has his/her utility function $U_i(r_{1i} + r_{2i} + ... + r_{Ki})$ that describes the type of traffic being handled by him/her smart phone. Our simulation determines the optimal rates that the $l^{th}$ carrier allocates to users under its coverage.

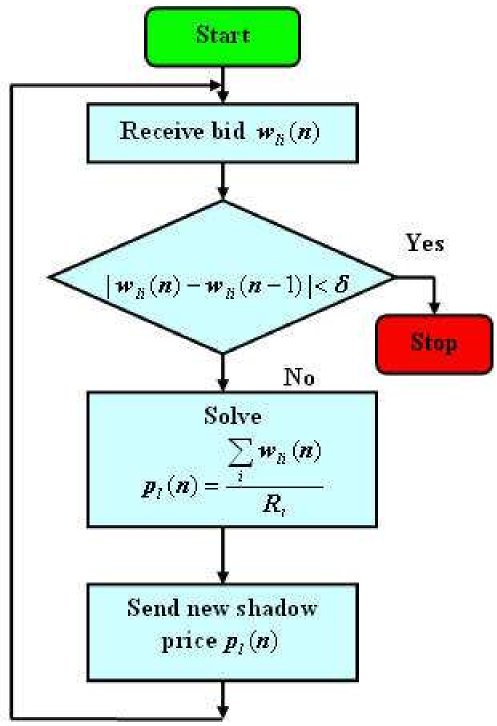


Figure 2.2: eNodeB Algorithm of Joint Carrier Aggregation

### 2.1.1 Algorithm of Joint Carrier Aggregation

The resource allocation with carrier aggregation algorithm in [2] allocates resources from multiple carriers simultaneously. The algorithm is divided into a $i^{th}$ UE algorithm shown in flow chart in Figure 2.3) and a $l^{th}$ eNodeB carrier algorithm shown in flow chart in Figure 2.2. In the allocation process shown in Figures 2.3 and 2.2 is as follows [2]:

- The $i^{th}$ UE starts with an initial bid $w_{li}(1)$ which is sent to the $l^{th}$ carrier eNodeB.

  In MATLAB:

```
% Initial Bids
w1 = [10 10 10 10 10 10 10 10 10 10 10 10];  % cell
    1 Carrier 1
```

```
w2 = [10 10 10 10 10 10 0 10 10 10 10 10];    % cell
    2 Carrier 2
```

- The $l^{th}$ eNodeB evaluates the difference between the received bid $w_{li}(n)$ and the previously received bid $w_{li}(n-1)$ and exits if and only if it is less than a provided threshold $\delta$.

  In MATLAB:

```
 while  (delta1 > 0.0001) && (delta2 > 0.0001) | (
    time<10)%
        :
        :
        :
        :
      delta1 = max(abs(w1-w1_old));
      delta2 = max(abs(w2-w2_old)) ;
end   % (while) end of the time iteration
```

- With $w_{li}(0) = 0$, if the value is greater than $\delta$, the $l^{th}$ eNodeB calculates $p_l(n) = \frac{\sum_{i=1}^{M} w_{li}(n)}{R_l}$ and sends that value to all the UEs in its coverage area.

  In MATLAB for first carrier:

```
function [p2] = eNodeB(w2)
global p_old R2
R2 = 100;
p2 = sum(w2)/R2;
```

  In MATLAB for second carrier:

```
function [p2] = eNodeB(w2)
global p_old R2
R2 = 100;
p2 = sum(w2)/R2;
```

```
p1(time) = eNodeB1varR(w1,Rate(i_rate));  % sent
   from eNodeB Carrier1
```

```
p2(time) = eNodeB2(w2);  % sent from eNodeB
    Carrier2

        %%%%%%%% solve for carrier 1
    soln1(ig3) = fzero(@(x) utility(x,ii,pp1),[.01
       1000]);
    if soln1(ig3) > r32_opt(ig3)
        soln1(ig3) = soln1(ig3) - r32_opt(ig3);
    else
        soln1(ig3) = 0;
    end
    r31_opt(ig3) = max(soln1(ig3), r31_min(ig3));
    w1(ig3) = r31_opt(ig3) * p1(time);
    %%%%%%%% solve for carrier 2
    soln2(ig3) = fzero(@(x) utility(x,ii,pp2),[.01
       1000]);
    if soln2(ig3) > r31_opt(ig3)
        soln2(ig3) = soln2(ig3) - r31_opt(ig3);
    else
        soln2(ig3) = 0;
    end
    r32_opt(ig3) = max(soln2(ig3), r32_min(ig3));
    w2(ig3) = r32_opt(ig3) * p2(time);
```

- The $i^{th}$ UE receives $p_l$ from in cell carriers and compares them to find the first minimum shadow price $p^1_{\min}(n)$ and its corresponding carrier $l_1 \in L$ where $L \in \{1, 2, ..., K\}$.

  In MATLAB:

```
p1(time) = eNodeB1varR(w1,Rate(i_rate));  % sent
    from eNodeB Carrier1
p2(time) = eNodeB2(w2);  % sent from eNodeB
    Carrier2

%%%%%%%% solve for carrier 1
    soln1(ig3) = fzero(@(x) utility(x,ii,pp1),[.01
       1000]);
```

```
    if soln1(ig3) > r32_opt(ig3)
    soln1(ig3) = soln1(ig3) - r32_opt(ig3);
    else
    soln1(ig3) = 0;
    end
    r31_opt(ig3) = max(soln1(ig3), r31_min(ig3));
    w1(ig3) = r31_opt(ig3) * p1(time);

    %%%%%%%% solve for carrier 2
    soln2(ig3) = fzero(@(x) utility(x,ii,pp2),[.01
       1000]);
    if soln2(ig3) > r31_opt(ig3)
    soln2(ig3) = soln2(ig3) - r31_opt(ig3);
    else
    soln2(ig3) = 0;
    end
    r32_opt(ig3) = max(soln2(ig3), r32_min(ig3));
    w2(ig3) = r32_opt(ig3) * p2(time);
```

- The $i^{th}$ UE solves the optimization sub-problem for the $l_1$ carrier rate $r_{l_1 i}(n)$ that maximizes $\log U_i(r_{1i} + ... + r_{Ki}) - \sum_{l=1}^{K} p_l(n) r_{li}$ with respect to $r_{l_1 i}$.

  In MATLAB:

```
%%% Group of users 1
for ig1 = 1: 2*length(a)
    pp11 = p1(time);
    ii1 =ig1;
    r1 = r1_opt(ii1);
    soln11(ig1) = fzero(@(x) utility(x,ii1,pp11)
       ,[.01 1000]);
    r1_opt(ig1) = max(soln11(ig1), r1_min(ig1));
    w1(ig1+6) = r1_opt(ig1) * p1(time);
    if abs(w1_old(ig1+6)-w1(ig1+6)) > (5.* exp
       (-0.1*time))%(10 ./ time)
    w1(ig1+6) = w1_old(ig1+6) + (5.* exp(-0.1*time)
       ) .* sign(w1(ig1+6)-w1_old(ig1+6));
```

```
    end
end
%%% Group of users 2
for ig2 = 1: 2*length(a)
    pp22 = p2(time);
    ii2 =ig2;
    r2 = r2_opt(ii2);
    soln22(ig2) = fzero(@(x) utility(x,ii2,pp22)
       ,[.01 1000]);
    r2_opt(ig2) = max(soln22(ig2), r2_min(ig2));
    w2(ig2+6) = r2_opt(ig2) * p2(time);
    if abs(w2_old(ig2+6)-w2(ig2+6)) > (5.* exp
       (-0.1*time))%(10 ./ time)
    w2(ig2+6) = w2_old(ig2+6) + (5.* exp(-0.1*time)
       ) .* sign(w2(ig2+6)-w2_old(ig2+6));
    end
end
%%% Group of users 3
for ig3 = 1: 2*length(a)
    pp1 = p1(time);
    pp2 = p2(time);
    ii =ig3;
    r31 = r31_opt(ii);
    r32 = r32_opt(ii);
end
```

In MATLAB:

```
%%%%%%%% solve for carrier 1

    soln1(ig3) = fzero(@(x) utility(x,ii,pp1),[.01
       1000]);
    if soln1(ig3) > r32_opt(ig3)
    soln1(ig3) = soln1(ig3) - r32_opt(ig3);
    else
    soln1(ig3) = 0;
    end
    r31_opt(ig3) = max(soln1(ig3), r31_min(ig3));
```

```
    w1(ig3) = r31_opt(ig3) * p1(time);

%%%%%%%% solve for carrier 2
    soln2(ig3) = fzero(@(x) utility(x,ii,pp2),[.01
       1000]);
    if soln2(ig3) > r31_opt(ig3)
    soln2(ig3) = soln2(ig3) - r31_opt(ig3);
    else
    soln2(ig3) = 0;
    end
    r32_opt(ig3) = max(soln2(ig3), r32_min(ig3));
    w2(ig3) = r32_opt(ig3) * p2(time);


if abs(w1_old(ig3)-w1(ig3)) > (5.* exp(-0.1*time))%
   (10 ./ time)
    w1(ig3) = w1_old(ig3) + (5.* exp(-0.1*time)) .*
         sign(w1(ig3)-w1_old(ig3));
end
if abs(w2_old(ig3)-w2(ig3)) > (5.* exp(-0.1*time))%
   (10 ./ time)
    w2(ig3) = w2_old(ig3) + (5.* exp(-0.1*time)) .*
         sign(w2(ig3)-w2_old(ig3));
end
```

- The rate $r_i^1(n) = r_{l_1 i}(n)$ is used to evaluate the new bid $w_{l_1 i}(n) = p^1_{\min}(n) r_i^1(n)$. The smart phone sends its new bid $w_{l_1 i}(n)$ to the $l_1$ carrier eNodeB.

```
 while  (delta1 > 0.0001) && (delta2 > 0.0001) | (
    time<10)%
     :
     :
     :
     :
         delta1 = max(abs(w1-w1_old));
         delta2 = max(abs(w2-w2_old)) ;
end   % (while) end of the time iteration
```

- Then, the smart phone selects the second minimum shadow price $p^2_{\min}(n)$ and its corresponding carrier index $l_2 \in L$.

- The smart phone solves for the $l_2$ carrier rate $r_{l_2 i}(n)$ that maximizes $\log U_i(r_{1i} + ... + r_{Ki}) - \sum_{l=1}^{K} p_l(n) r_{li}$ with respect to $r_{l_2 i}$. The rate $r_{l_2 i}(n)$ subtracted by the rate from $l_1$ carrier $r_i^2(n) = r_{l_2 i}(n) - r_i^1(n)$ is used to calculate the new bid $w_{l_2 i}(n) = p^2_{\min}(n) r_i^2(n)$ which is sent to $l_2$ carrier.

- In general, the smart phone selects the $m^{th}$ minimum shadow price $p^m_{\min}(n)$ with carrier index $l_m \in L$ and solves for the $l_m$ carrier rate $r_{l_m i}(n)$ that maximizes $\log U_i(r_{1i} + ... + r_{Ki}) - \sum_{l=1}^{K} p_l(n) r_{li}$ with respect to $r_{l_m i}$.

- The rate $r_{l_m i}(n)$ subtracted by $l_1, l_2, ..., l_{m-1}$ carriers rates $r_i^m(n) = r_{l_m i}(n) - (r_i^1(n) + r_i^2(n) + ... + r_i^{m-1}(n))$ is used to evaluate the new bid $w_{l_m i}(n) = p^m_{\min}(n) r_i^m(n)$ which is sent to $l_m$ carrier.

  In MATLAB:

```
soln(i) = fzero(@(x) utility(x,ii,pp,time),[.001
   1000000]);
```

- Avoiding fluctuation.

  In MATLAB:

```
if abs(w1_old(ig3)-w1(ig3)) > (5.* exp(-0.1*time))%
   (10 ./ time)
     w1(ig3) = w1_old(ig3) + (5.* exp(-0.1*time)) .*
         sign(w1(ig3)-w1_old(ig3));
end
if abs(w2_old(ig3)-w2(ig3)) > (5.* exp(-0.1*time))%
   (10 ./ time)
     w2(ig3) = w2_old(ig3) + (5.* exp(-0.1*time)) .*
         sign(w2(ig3)-w2_old(ig3));
end
```

- This process is repeated until $|w_{li}(n) - w_{li}(n-1)|$ is less than the threshold $\delta$.

  In MATLAB:

```
while  (delta1 > 0.0001) && (delta2 > 0.0001) | (
   time<10)   :
    :
    :
    :
        delta1 = max(abs(w1-w1_old));
        delta2 = max(abs(w2-w2_old)) ;
end   % (while) end of the time iteration
```

The transmission Digram is shown in Figure 2.4.

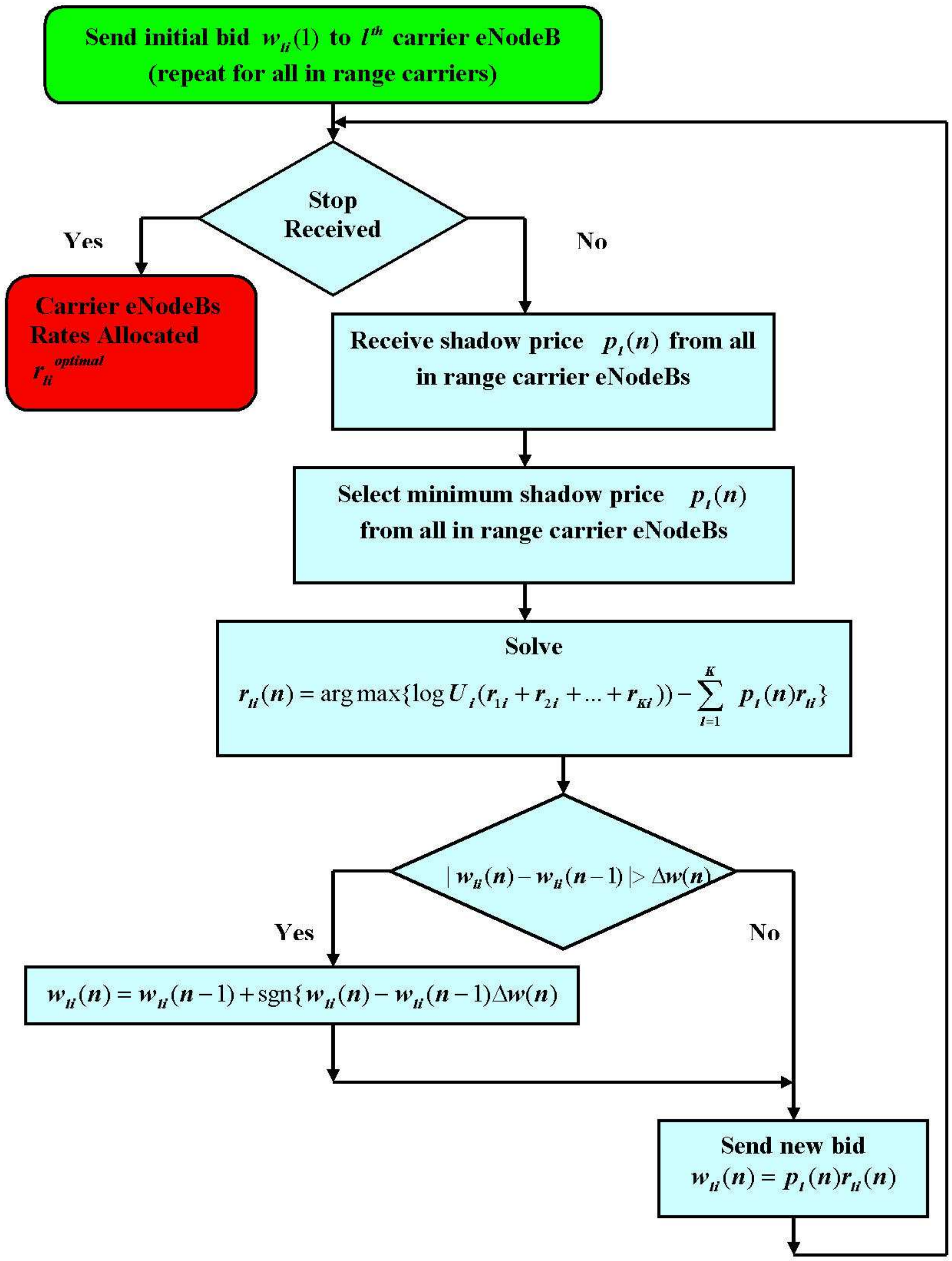


Figure 2.3: UE Algorithm of Joint Carrier Aggregation

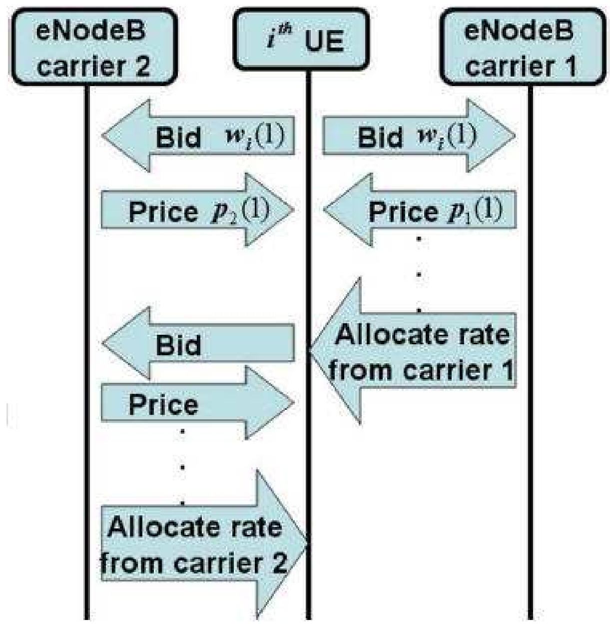


Figure 2.4: Transmission of Joint Carrier Aggregation

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