Chapter 2
Utility Functions and Radio Resource Allocation

The world of radio resource allocation for wireless communications has had numerous directions relying chiefly on miscellaneous methods from linear algebra, machine learning, queuing theory, and so forth. An overwhelming of QoS-based radio resource allocation works that have been formulated as optimization problems in the realm of linear algebra and leverage application utility functions to define traffic requirements. Thus, a rudimentary familiarity of the application utility functions and optimization theory is consequential to understanding the radio resource allocation mechanisms introduced in this book. In this regard, this chapter presents the background information on material needed to understand the work in this book. Furthermore, a literature survey of the salient radio resource allocation methods is presented in Sect. 2.3 of this chapter. In this chapter

- We provide with the background information on application utility functions as an application QoS modeling measure.
- We present some popular resource allocation formulations in the context of cellular communications systems.
- we introduce fundamentals of the Frank Kelly Algorithm.
- we develop a literature survey on topical research papers about resource allocation in mobile systems.

The rest of this chapter proceeds as follows. Section 2.1 introduces application utility functions; Sect. 2.2 presents resource allocation formulations and presents two prevalent proportional fairness and max-min techniques germane to resource allocation. Section 2.3 illustrates a literature survey about resource allocation in modern cellular communications systems. Formulation of utility functions and QoS appears in recent works such as [1–6]

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2.1 Application Utility Functions

Application utility functions have been used in a wide variety of researches which model characteristic features of the system. For example, [8, 9] leveraged utility functions to model the modulation schemes in a power allocation problem. Additionally, sensors with prespecified utility functions can ensure optimal performance for machine-to-machine communications system [10–15] which outperform conventional schedulers [16–18]. For modern cellular network, resource of applications running on the smart devices should account for QoS requirements for the traffic generated by the running applications. The degree to which the QoS requirements of application traffic are fulfilled can be expressed by the concept of application utility function, which maps a feasible rate allocation to a utility function value that is the QoS fulfillment percentage for that particular application.

There exists little evidence about the precise shape of application utility functions [19–22]; however, we can conjecture about their qualitative behaviors. Traditional applications such as File Transfer Protocol (FTP) and Simple Mail Transfer Protocol (SMTP) applications produce elastic traffic characterized by adapting its rate in the face of congestion and delays in the network [23, 24]. Applications producing such an elastic traffic are delay-tolerant. Intuitively, the QoS satisfaction for delay-tolerant applications has a decreasing marginal return for an increasing rate allocation.

The application utility functions modeling the QoS satisfaction of the elastic traffic generated by delay-tolerant applications look like Fig. 2.1. Here, we can observe a decreasing return in the value of the application utility function as the allocated rate is increased. As we can see, the application utility function is convex everywhere

Other applications like telephony generate an inelastic traffic which needs rate in order to arrive within a given delay bound even though it does not care if the data arrives earlier. The application performs poorly if the data packets arrive later than the delay bound. Such applications, denoted as real-time applications, are mainly those expecting circuit-switched services and ask for a minimum throughput before observing an acceptable performance. The application utility function for the inelastic traffic produced by real-time applications is like Fig. 2.2, from which we can observe

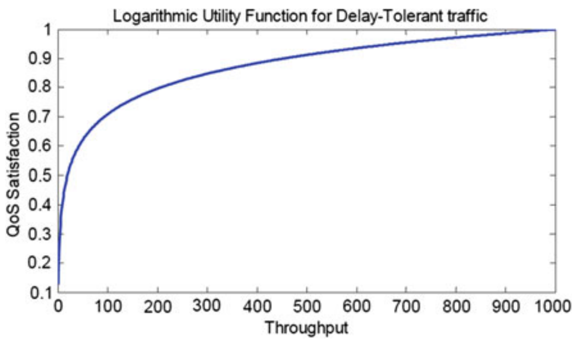

Fig. 2.1 Utility function $U(x)$ for delay-tolerant applications versus rate allocation x

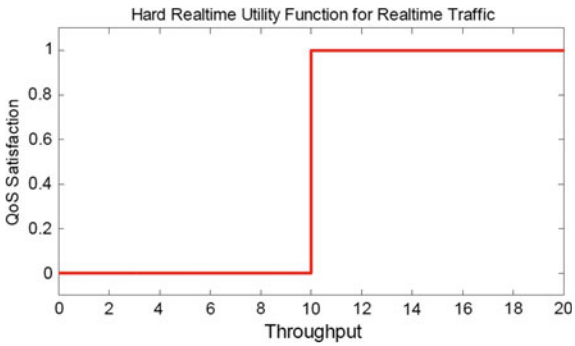

Fig. 2.2 Utility function $U(x)$ for hard real-time applications versus rate allocation x

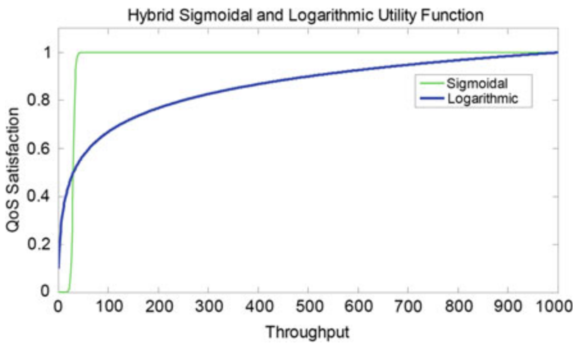

Fig. 2.3 Utility function $U(x)$ for soft real-time applications versus rate allocation x

so long as the delay bounds are met,the performance is satisfaction almost constant while once the throughput drops below what is required to meet the required delay bounds, the performance plummets to zero sharply.

While audio and video applications have hard requirements, they can be implemented to be rather tolerant of occasional delay/packet loss violations. The intrinsic throughput requirements for real-time applications are due to the fact that the inelastic traffic data generation rate is independent of network congestion. Hence, the QoS performance degrades severely as the share for the application becomes less than the intrinsic generation rate for that traffic. Such soft real-time applications can have utility functions like Fig. 2.3.

Here, the performance satisfaction is mainly constant after meeting the delay bounds whereas it drops close to zero when the application throughput goes below what is needed to meet the delay bounds. In comparison to hard real-time applications, the performance deterioration of the delay-adaptive, real-time application is not as dramatic as the hard real-time application depicted in Fig. 2.2. As we can observe, the shape of the utility is convex in the vicinity of zero and is concave after the minimum throughput for the application is realized. From now on, unless it is explicitly stated, this book refers to an application performance satisfaction as a function of rate as application utility function, which is denoted as $U(r)$ for the allocated rate r. Application utility functions have the following main properties [25–27].

- $U(0) = 0$.
- $U(r)$ is an increasing function r.
- $U(r)$ is twice differentiable in r.
- $U(r)$ is upper-bounded.

The first and the second statements of the properties imply the nonnegativity of the application utility functions. This is expected as they represent application performance satisfaction whereas the third and fourth statements reveal the more assigned the rates, the higher the satisfaction for the application performance. On the other hand, the third and fourth predicate indicate that the application utility functions are continuous. A hybrid traffic includes both inelastic and elastic traffic streams emerged from real-time and delay-tolerant applications, whose QoS is conducively modeled by sigmoidal and logarithmic utility functions in Eqs. (2.2) and (2.1) in that order [28, 29].

$$U(r) = c\Big(\frac{1}{1 + e^{-a(r-b)}} - d\Big) \tag{2.1}$$

Here, $d = \frac{1}{1+e^{ab}}$ and $c = \frac{1+e^{ab}}{e^{ab}}$. It can be verified that $U(\infty) = 1$ and $U(0) = 0$, where the latter is one of the formerly mentioned utility function properties and the former indicates that an infinite resource assignment leads to 100 % satisfaction. Moreover, it can be derived that the inflection point of the function in Eq. (2.1) is at $r = r^{\text{inf}} = b$ where the superscript "inf" stands for "infliction." This can be done by differentiating $U(r)$ with respect to r twice and setting the second derivative equal to zero, i.e., $\frac{\partial^2 U}{\partial r^2} = 0 \rightarrow r = b$.

Here, $r^{\max}$ is the maximum rate where the application QoS is satisfied fully (100 % utility) and k is the utility function increase with increasing the rate r. It can be investigated that $U(r^{\max}) = 1$ and $U(0) = 0$ where the latter is the basic property of the utility functions and the former indicates that a 100 % QoS satisfaction is at $r = r^{max}$. The normalized logarithmic function inflection point occurs at $r = r^{\text{inf}} = 0$.

$$U(r) = \frac{\log(1 + kr)}{\log(1 + kr^{\max})} \tag{2.2}$$

The application utility functions with the parameters in Table 2.1 are considered. Here, the sigmoidal application utility with parameter $a = 1, b = 25$ estimate another real-time application with the inflection point $r = 25$ which suites high definition video streaming. Moreover, the logarithmic application utility functions with $r^{\max} = 100$ and different k_i parameters approximate delay-tolerant FTP applications.

The application utility functions with parameters in Table 2.1 are shown in Fig. 2.4. We can see that the real-time applications need a minimum rate, which is the inflection point beyond that the application QoS is fulfilled to a large degree. The logarithmic application utility function is provided with certain QoS at low rates appropriate for the delay-tolerant applications. Furthermore, we can see from Fig. 2.4 that the plotted utility functions are strictly increasing continuous functions and are zero

Table 2.1 Example applications utility function parameters

Applications utilities parameters—diagrams in Fig. 2.4	
Real-time	Sigmoid $a = 1, \quad b = 25$
Delay-tolerant	Logarithmic $k = 15, \quad r^{\max} = 100$

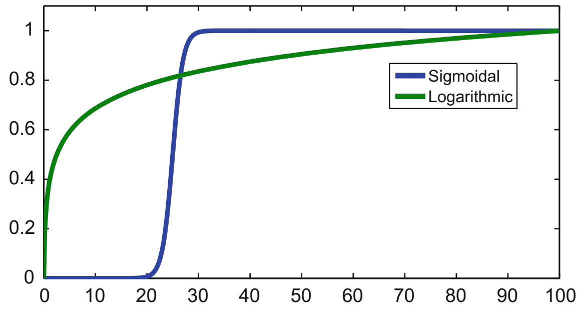

Fig. 2.4 Delay-tolerant and real-time applications have respectively logarithmic and sigmoidal utility functions U_{ij} plotted against the application-assigned rates r_{ij}. Here, the sigmoidal application utility with parameter $b = 25$ is a good model for high definition video streaming

valued for zero rates. These comply the aforementioned mathematical properties for the application utility functions.

Because sigmoidal utility functions gain a slight QoS satisfaction only after the allocated rates exceed the utility functions inflection points whereas the logarithmic utility functions get some QoS fulfillment even for a small throughput, these behaviors bring about sigmoidal and logarithmic utility functions appropriate models for real-time and delay-tolerant applications QoS satisfaction respectively. Mathematical analyses germane to this matter appear in [28, 30–32] in more details.

Next, Sect. 2.2 explains some points regarding various factors that affect resource allocation formulation.

2.2 Resource Allocation Formulations

In the mathematics literature germane to utility functions and resource allocation, a wide variety of formulations have been presented and numerous solutions have been proposed. Amidst various formulations, max-min fairness [33–40] and proportional fairness [41] have received attention as they can yield in optimal and/or efficient solutions [42–44]. Moreover, the authors in [45–47] define a solution to be either Pareto inefficient, Pareto optimal, or infeasible solutions. The last item indicate that an allocation is not feasible based on the resources available and the network demand. However, [45] defined Pareto inefficiency as a rate assignment which does not assign resources and it also defines Pareto optimality as assigning all available resources. In the resource allocation work in Chaps. 3 and 4 of this book, we will be leveraging formulations leading to Pareto optimal solutions.

2.2.1 Max-Min Resource Allocation

A feasible resource allocation achieves max-min fairness if an attempt for increasing a rate assignment to an entity in the system leads to reducing the assignment in another entity which do not have more resources than the entity which got more resources. Hence, this method obtains the highest utility value with the lowest values of utility [45, 48, 49]. Using max-min fairness, we can shape the traffic, versus a First-Come First-Serve (FCFS) multiplexing, by not allowing a heavy flow of large packages block serving other flows in the network. In particular, for the utility function $U(r)$ where r is the allocated rate, the max-min fairness can be formalized as Eq. (2.3). Water filling [50–52] can be deployed to solve the max-min fairness problems. [33] proved that a max-min fairness policy cannot deal with bottlenecks in the network. Next, we look at the proportional fairness policy for resource allocation.

$$r = argmax_r min_r U(r) \tag{2.3}$$

2.2.2 Proportional Fairness

A feasible resource allocation achieves proportional fairness if it maximizes the system overall utility while providing with a minimal service to system entities needing resources. This is performed by assigning each flow a rate inversely proportional to its resource need [53, 54]. For the utility function $U_i(r_i)$, where r_i is the allocated rate to the i^{th} UE, proportional fairness can be formalized as Eq. (2.4). According to the properties of application utility functions in Sect. 2.1, we see that $U_i(r_i = 0) = 0$ which zeros the system utility, i.e., $\prod_{i=1}^{N} U_i(r_i)$. So, no UE will be assigned a zero rate under this formulation. Various methods of solving proportional fairness optimizations have been introduced in literature and the salient of them are the Weighted Fair Queuing (WFQ) [55–57] and Frank Kelly algorithm [58]. Frank Kelly algorithm is an iterative that allows UEs bid for resources until the algorithm reaches optimal allocation and the shadow price (amount of consumed resources per data bit) [58]. On the other hand, proportional fairness can be obtained by setting the inverse shadow price as the weights used for the WFQ. We will be using a proportional fairness formulation for our radio resource allocation work presented in Chaps. 3 and 4. However, we would tailor the formulation to include UE priorities and application temporal usage percentages in addition to the application utility function constituents which represent the traffic.

$$r_i = argmax_{r_i} \prod_{i=1}^{N} U_i(r_i) \tag{2.4}$$

2.2.3 Frank Kelly Algorithm

Frank Kelly algorithm was a seminal work to achieve proportional fairness and was introduced in [58]. [58] proved that their method brings about Pareto optimal resource allocation for a proportional fairness formulation. In accordance to [58], the procedure commences as UEs send their bids w_i to a resource allocation manager entity that obtains the shadow price as addition of the bids averaged on the whole resources R available for the manager entity, i.e., $p = \frac{\sum_i^N w_i}{R}$. The bids to the shadow price ratio, $r_i = \frac{w_i}{p}$, derives the rates. Next, users check whether the rate are optimal by solving $r_{i,textopt} = \arg\max_{r_i}\Big(U_i(r_i) - pr_i\Big)$ and if $r_i \neq r_{i,\text{opt}}$, they transmit new bids $w_i = r_{i,\text{opt}}p$ to the resource allocation manager and the procedure iterates until a convergence occurs; that is the utility function derivative equals the shadow price $\frac{\partial U_i}{\partial r_i}|_{r_i=r_{i,\text{opt}}} = p$ [45, 58]. This procedure is summarized in Algorithm 1. We will be using a method based on the Frank Kelly algorithm to solve the proportional fairness resource allocation formulation that will be developed in Chaps. 3 and 4 of the book.

Algorithm 1 Frank Kelly Algorithm

```
Send initial bid w_i(n = 1) to the resource allocation managing entity.
loop
  Calculate shadow price p(n) = (sum_i^N w_n) / R.
  Receive shadow price p(n) from the resource allocation managing entity.
  Calculate allocated rate r_i = w_i(n) / p(n).
  Solve r_{i,opt} = arg max_{r_i} ( U_i(r_i) - p(n) r_i ).
  if r_i ≠ r_{i,opt} then
    Calculate w_i = r_{i,opt} p.
    Send the bid w_i(n) to the resource allocation managing entity.
  end if
end loop
```

Next, Sect. 2.3 presents the previous studies about radio resource allocation.

2.3 Previous Studies on Resource Allocation

The resource allocation optimization research area has received a significant interest after the seminal network utility maximization study in [58] which assigned UE rates via a utility proportional fairness maximization solved by the Lagrange Multipliers [59]. Soon after, an iterative solution algorithm based on the optimization duality was proposed [60–62]. While the traffic in these early research works had an elastic nature which was common for wired communication systems and are modeled by concave utility functions, the emergence of high-speed wireless networks have entailed produced an increased usage of real-time applications whose utility functions are non-concave [25]. For example, the utility of a VoIP application can be modeled as a step function whose utility is zero before a threshold rate and achieves 100 % for rates larger than the threshold. Another example is a video streaming application for which the utility function is a sigmoidal function convex/concave for rates below/above its inflection point. As such, the approaches presented in [58, 60] have the proceeding drawbacks: (a) Reaching optimal solutions for concave utility functions, these are not applicable to the escalating inelastic traffic volume of modern networks; (b) Neither do they render any priority to real-time applications with stringent QoS requirements, nor they give any attention for the application usage changes, nor they attend to subscribers varied importance which pivotal from a business standpoint.

Later, the authors in [28, 63, 64] introduced distributed rate allocation algorithms based on concave and sigmoidal utility functions representing applications. Despite approximating optimal solution closely, the proposed methods dropped UEs to maximize the system utility and could not guarantee a minimal QoS. The authors in [65–67] proposed a utility proportional fairness resource allocation for a single carrier communications system and cast the formulation as a convex optimization with logarithmic and sigmoidal utility functions modeling delay-tolerant and real-time applications respectively. Even though their schemes prioritized the real-time applications over the delay-tolerant applications, they neither considered the application status or UE differentiation treatments, nor they regarded the hybrid traffic common in modern communications networks.

The authors in [68, 69] and [70–72] considered a similar multicarrier optimal resource allocation aware of the subscriber priorities. However, no attention was rendered to the temporal changes in the application usage or UE quantities. In [73], the authors adopted a non-convex optimization formulation to maximize the system utility in wireless networks consisting of applications with logarithmic and sigmoidal utility functions. A distributed process was employed to obtain the rates under a zero duality gap; but, the algorithm did not converge for a positive duality gap leading to compounding a heuristic to ensure the network stability. In [45], the author considered a weighted aggregation of logarithmic and sigmoidal utilities approximated to the nearest concave utility function via a minimum mean-squared error measure inside UEs. The approximate utility function solved the rate allocation optimization through a variation of the conventional distributed resource allocation approach in [58] such that rate assignments essentially estimated optimal ones. However, the rate were only approximations and no consideration was given to user or application priorities. This work was extended by Shajaiah et al. [74, 75] to allow for the application of the resource allocation in a multicarrier network in public safety.

In a similar work [76–78], the authors proposed a utility proportional fairness optimization which assigned optimal UE rates in a cellular infrastructure coexistent with radars by leveraging the Lagrange multipliers. [79–82] presented a subcarrier allocation in orthogonal frequency division multiplexed systems focusing on delay constrained data and leveraged network delay models [83–85] for the subcarrier assignment. The authors of [86, 87] created a utility max-min fairness for the hybrid traffic which share a single path in a communications network. Similarly, [30, 88, 89] presented a utility proportional fairness optimization for the high signal-to-interference-plus-noise ratio (SINR) wireless networks using a utility max-min formulations, contrasted against the proportional fairness algorithms [90–93] and gave a closed-form solution that eschewed from network oscillations. However, neither methods cared for any traffic or user priorities in assigning the spectrum. In [7, 94, 95], the authors created a utility proportional fairness resource block allocation as an integer optimization problem. They obtained the continuous optimal rates and then took on a boundary mapping technique to extracted a pool of valid resource blocks tantamount to inferred optimal continuous rates, albeit neither hybrid traffic, nor application status, nor user importance was accounted for. The authors of [96] investigated the WiMAX-radar mutual interference and concluded that large geographic separations between the two systems are required, precluding WiMAX deployability in the coastline. Cotton et al. [97–102] performed tests, using a shipborne radar in San Diego littoral waters, measuring the temporal band occupancy and found that the 3.5 GHz spectrum is not often occupied by radar transmissions, underlining the potential of the germane band for spectrum sharing. Lackpour et al. [103] suggested a general spectrum sharing scheme based on time, space, frequency, and system-level modifications, inappropriate to real-world implementation. Sanders et al. [104] performed experiments with RF hardlines to observe the interference effects from radar waveforms into a 3.5 GHz LTE base station (BS). They observed the throughput loss and block error rate (BLER) for the LTE system in the UL direction; however, their results were varied as some waveforms did not have any effect on the LTE while others undermined the performance drastically. Neither did they consider any propagation models, nor did they perform any simulation of realistic radar or LTE system. Furthermore, Bjornson has extensively written on resource allocation [105–113], and a lot of theoretical contributions are provided by [64, 114–123, 123–125]. And last but not the least, [87] proposed a context-aware source allocation in cellular networks; but, they did not consider the temporal changes in the application usage percentage, the number of UEs in the system, or subscribers' priority.

2.4 Chapter Summary

In this chapter, we introduced the concept of application utility functions and their relationship to satisfying the QoS requirement of various delay-tolerant and real-time applications. We illustrated appropriate mathematical models for the application utility functions of real-time and delay-tolerant applications as respectively sigmoidal and logarithmic utility functions. Furthermore, we explained about prevalent resource allocation frameworks in modern resource allocation studies in cellular systems. We introduced max-min and proportional fairness optimizations as common approaches to resource allocation optimization formulation. And, we provided a literature survey on topical resource allocation works in the context of cellular communications systems.

2.5 MATLAB Code

The following code plots the application utility functions given in Fig. 2.4. Lines 1–12 initializes the parameters of the application utility functions according to Table 2.1. This code requires the Symbolic Toolbox of MATLAB. If the reader does not have access to this toolbox, you should declare x as a vector such as $x = 0.1 : 1000$; and eliminate "syms x."

```
1  syms x
2  k = 15;
3  a = 1;
4  b = 25;
5  c = (1 + exp(a .* b)) ./ (exp(a .* b));
6  d = 1 ./ (1 + exp(a .*b));
7  s
8  %%%%Application Utility Functions%%%%%
9  for i = 1: length(a)
10
11     % Sigmoid utility function
12     y(i) = c(i).*(1./(1+exp(-a(i).*(x-b(i))))-d(i));
13
14     % Logarithmic utility function
15     y2(i) = log(k(i).*x+1)./(log(k(i).*100+1));
16     m(i) = exp(-a(i).*(x-b(i)));
17     dy_log(i) = k(i)./((1+k(i).*x).*log(1+k(i).*x));
18 end
19
20 %%%%%%%%%%%%%%%%Plot%%%%%%%%%%%%%%%%%%
21 yy(1) = 0;
22 yy2(1) = 0;
23 for j = 2:1: 1000
24     x0(j) = 0.1 * j ;
25     yy(j) = subs(y(i),x0(j));
26     yy2(j) = subs(y2(i),x0(j));
27 end
28 plot(x0,yy,x0,yy2);
29 legend('Sigmoidal', 'Logarithmic');
```

References

1. Ghorbanzadeh M, Chen Y, Ma Z, Clancy C (2013) A neural network approach to category validation of android applications. IEEE international conference on computing, networking and communications (ICNC)
2. Chen Y, Ghorbanzadeh M, Ma K, Clancy C, McGwier R (2014) A hidden markov model detection of malicious android applications at runtime. 23rd conference on wireless and optical communication (WOCC)

3. Ghorbanzadeh M, Visotsky E, Moorut P, Yang W, Clancy C (2015) Radar inband and out-of-band interference into LTE macro and small cell uplinks in the 3.5 GHz band. IEEE conference on wireless communications and networking (WCNC)
4. Ghorbanzadeh M, Visotsky E, Moorut P, Yang W, Clancy C (2015) Radar in-band interference effects on macrocell LTE uplink deployments in the US 3.5 GHz band. IEEE international conference on computing, networking and communications (ICNC)
5. Ghorbanzadeh M, Visotsky E, Moorut P, Clancy C (2016) Radar interference into LTE base stations in the 3.5 GHz band. Phys Commun
6. Abdelhadi A, Clancy C, Mitola J (2013) A resource allocation algorithm for users with multiple applications in 4G-LTE. CRAB '13 proceedings of the 1st ACM workshop on cognitive radio architectures for broadband
7. Ghorbanzadeh M, Abdelhadi A, Clancy C (2015) A utility proportional fairness radio resource block allocation in cellular networks. In: IEEE international conference on computing, networking and communications (ICNC)
8. Kbah Z, Abdelhadi A (2015) Resource allocation in cellular systems for applications with random parameters. CoRR
9. Abdel-Hadi A, Michel J, Gerstlauer A, Vishwanath S (2011) Real-time optimization of video transmission in a network of aavs. In: Vehicular technology conference (VTC Fall), 2011 IEEE, pp 1–5
10. Kumar A, Abdelhadi A, Clancy TC (2016) A delay optimal MAC and packet scheduler for heterogeneous M2M uplink. CoRR vol abs/1606.06692
11. Hossain E, Han Z, Poor HV (2012) Smart grid communications and networking. Cambridge University Press
12. Kumar A, Abdelhadi A, Clancy TC An online delay-optimal iterative multiclass scheduler for generic M2M uplink (under submission)
13. Gotsis A, Lioumpas A, Alexiou A (2012) Evolution of packet scheduling for machine-type communications over LTE: algorithmic design and performance analysis. In: IEEE globecom workshop, pp 1620–1625
14. Kumar A, Abdelhadi A, Clancy TC (2016) A delay-optimal packet scheduler for M2M uplink. IEEE MILCOM
15. Nielsen JJ, Madueo GC, Pratas NK, Srensen RB, Stefanovic C, Popovski P (2015) What can wireless cellular technologies do about the upcoming smart metering traffic? IEEE Commun Mag 53:41–47
16. Nagle J (1987) On packet switches with infinite storage. IEEE Trans Commun 35:435–438
17. Parekh AK, Gallager RG (1993) A generalized processor sharing approach to flow control in integrated services networks: the single-node case. IEEE/ACM Trans Netw 1:344–357
18. Shreedhar M, Varghese G (1996) Efficient fair queuing using deficit round-robin. IEEE/ACM Trans Netw 4:375–385
19. Wilson F, Wakeman I, Smith W (1993) Quality of service parameters for commercial application of video telephony. In: Human facotrs telecommunications symposium
20. Aggarwal A, Meng T (2006) Minimizing the peak-to-average power ratio of ofdm signals using convex optimization. IEEE Trans Signal Process
21. Al-Shatri H, Weber T (2012) Achieving the maximum sum rate using D.C. programming in cellular networks. IEEE Trans Signal Process
22. Abdelhadi A, Gerstlauer A, Vishwanath S (2014) Real-time rate-distortion optimized streaming of wireless video. CoRR
23. Annapureddy V, Veeravalli V (2011) Sum capacity of MIMO interference channels in the low interference regime. IEEE Trans Inf Theory
24. Abdelhadi A, Clancy T (2015) An optimal resource allocation with frequency reuse in cellular networks
25. Shenker S (1994) Fundamental design issues for the future internet. IEEE J Sel Areas Commun
26. Abdel-Hadi A, Vishwanath S (2010) On multicast interference alignment in multihop systems. In: IEEE information theory workshop 2010 (ITW 2010)

27. Jose J, Abdel-Hadi A, Gupta P, Vishwanath S (2010) On the impact of mobility on multicast capacity of wireless networks. In: INFOCOM, 2010 Proceedings IEEE, pp 1–5
28. Lee J, Mazumdar R, Shroff N (2005) Downlink power allocation for multi-class wireless systems. IEEE/ACM Trans Netw
29. Wang Y, Abdelhadi A (2015) A qos-based power allocation for cellular users with different modulations. CoRR vol abs/1507.07141
30. Tychogiorgos G, Gkelias A, Leung K (2012) Utility proportional fairness in wireless networks. In: IEEE international symposium on personal, indoor, and mobile radio communications (PIMRC)
31. Wang Y, Abdelhadi A (2015) Optimal power allocation for lte users with different modulations. CoRR vol abs/1507.07159
32. Abdelhadi A, Khawar A, Clancy TC (2014) Optimal downlink power allocation in cellular networks. CoRR vol abs/1405.6440
33. Li M, Chen Z, Tan Y (2011) A maxmin resource allocation approach for scalable video delivery over multiuser mimo-ofdm systems. In: IEEE international symposium on circuits and systems (ISCAS)
34. Khawar A, Abdelhadi A, Clancy TC (2015) Channel modeling between seaborne MIMO radar and MIMO cellular system. CoRR vol abs/1504.04325
35. Lee RMJ-W, Mandayam NB (2015) A utility based approach for multi-class wireless systems. IEEE/ACM Trans Netw 13:854–867
36. Ahmed S, Thompson JS, Mulgrew B, Petillot Y (2010) Constant envelope waveform design for MIMO radar. In: International conference on acoustics, speech, and signal processing, pp 4066–4069
37. Khawar A, Abdelhadi A, Clancy TC (2015) 3d channel modeling between seaborne MIMO radar and MIMO cellular system. CoRR vol abs/1504.04333
38. Marbach P, Berry R (2002) Downlink power allocation and pricing for wireless networks. Proceedings of IEEE INFOCOM 3:1470–1479
39. Ahmed S, Thompson JS, Petillot YR, Mulgrew B (2011) Finite alphabet constant-envelope waveform design for MIMO radar. IEEE Trans Signal Process 59(11):5326–5337
40. Khawar A, Abdelhadi A, Clancy TC (2015) Coexistence analysis between radar and cellular system in LoS channel. CoRR vol abs/1506.07468
41. Andrews M, Kumaran K, Ramanan K, Stolyar A, Whiting P, Vijayakumar R (2001) Providing quality of service over a shared wireless link. IEEE Commun Mag
42. Fudenberg D, Tirole J (1991) Nash equilibrium: multiple nash equilibria, focal points, and pareto optimality. MIT Press
43. Shahriar C, Abdelhadi A, Clancy TC (2015) Overlapped-mimo radar waveform design for coexistence with communication systems. CoRR vol abs/1502.04117
44. Khawar A, Abdel-Hadi A, Clancy T, McGwier R (2014) Beampattern analysis for mimo radar and telecommunication system coexistence. In: 2014 international conference on computing, networking and communications (ICNC), pp 534–539
45. Kurrle R (2012) Resource allocation for smart phones in 4G-LTE advanced carrier aggregation. Master Thesis, Virginia Tech
46. Khawar A, Abdelhadi A, Clancy T (2014) A mathematical analysis of cellular interference on the performance of s-band military radar systems. In: Wireless telecommunications symposium (WTS), pp 1–8
47. Babaei A, Tranter WH, Bose T (2013) A practical precoding approach for radar/communications spectrum sharing. In: Cognitive radio oriented wireless networks (CROWNCOM), pp 13–18
48. Ariaudo M, Fijalkow I, Gautier J, Brandon BAM, Milevsky B (2012) Green radio despite dirty RF front-end. IEEE Trans Inf Theory
49. Bagherikaram AG, Motahari S, Khandani AK (2009) The secrecy capacity region of the Gaussian MIMO broadcast channel. IEEE Trans Inf Theory
50. Prabhu R, Daneshrad B (2010) An energy-efficient water-filling algorithm for ofdm systems. In: IEEE international conference on communications (ICC)

51. Balakrishnan V, Boyd S, Balemi S (1991) Robust downlink beamforming based on outage probability specifications. Int J Robust Nonlinear Control
52. Khawar A, Abdelhadi A, Clancy C (2015) Target detection performance of spectrum sharing mimo radars. Sens J IEEE 15:4928–4940
53. Kushner H, Whiting P (2004) Convergence of proportional-fair sharing algorithms under general conditions. IEEE Trans Wirel Commun
54. Shajaiah H, Khawar A, Abdel-Hadi A, Clancy T (2014) Resource allocation with carrier aggregation in lte advanced cellular system sharing spectrum with s-band radar. In: 2014 IEEE international symposium on dynamic spectrum access networks (DYSPAN), pp 34–37
55. Parekh A, Gallager R (1993) A generalized processor sharing approach to flow control in integrated services networks: the single-node case. IEEE/ACM Trans Netw
56. Demers A, Keshav S, Shenker S (1989) Analysis and simulation of a fair queueing algorithm. SIGCOMM Comput Commun Rev
57. Khawar A, Abdelhadi A, Clancy TC (2014) On the impact of time-varying interference-channel on the spatial approach of spectrum sharing between S-band radar and communication system. In: Military communications conference (MILCOM)
58. Kelly F, Maulloo A, Tan D (1998) Rate control in communication networks: shadow prices, proportional fairness and stability. J Oper Res Soc
59. Boyd S, Vandenberghe L (2004) Introduction to convex optimization with engineering applications. Cambridge University Press
60. Low S, Lapsley D (1999) Optimization flow control, i: basic algorithm and convergence. IEEE/ACM Trans Netw
61. de Kerret P, Gesbert D The multiplexing gain of the network MIMO channel with distributed CSI. arXiv:1108.3742 (to apprear)
62. Ghorbanzadeh M, Abdelhadi A, Clancy C (2014) A utility proportional fairness resource allocation in spectrally radar-coexistent cellular networks. In: Military communications conference (MILCOM)
63. Lee J, Mazumdar R, Shroff N (2005) Non-convex optimization and rate control for multi-class services in the internet. IEEE/ACM Trans Netw
64. Shajaiah H, Abdelhadi A, Clancy C (2015) Spectrum sharing approach between radar and communication systems and its impact on radar's detectable target parameters. In: Vehicular technology conference (VTC Spring), 2015 IEEE 81st, pp 1–6
65. Abdelhadi A, Clancy C (2014) A utility proportional fairness approach for resource allocation in 4G-LTE. In: IEEE international conference on computing, networking, and communications (ICNC), CNC workshop
66. Abdelhadi A, Clancy C (2013) A robust optimal rate allocation algorithm and pricing policy for hybrid traffic in 4G-LTE. In: IEEE international symposium on personal, indoor, and mobile radio communications (PIMRC)
67. Abdelhadi A, Clancy C, Mitola (2013) A resource allocation algorithm for users with multiple applications in 4G-LTE. In: ACM workshop on cognitive radio architectures for broadband (MobiCom workshop CRAB)
68. Han M, Yu T, Kim J, Kwak K, Lee S, Han S, Hong D (2008) OFDM channel estimation with jammed pilot detector under narrow-band jamming. IEEE Trans Veh Technol
69. Ghorbanzadeh M, Abdelhadi A, Clancy T (2015) A utility proportional fairness approach for resource block allocation in cellular networks. In: IEEE International conference on computing, networking and communications (ICNC)
70. Shajaiah H, Abdelhadi A, Clancy C (2014) Multi-application resource allocation with users discrimination in cellular networks. In: IEEE international symposium on personal, indoor and mobile radio communications
71. Guo F, Chenggui W (2008) A jamming scheme based on pilot assisted channel estimation of OFDM. J Electron Warfare Technol
72. Khawar A, Abdel-Hadi A, Clancy TC (2014) MIMO radar waveform design for coexistence with cellular systems. In: IEEE international symposium on dynamic spectrum access networks: SSPARC workshop (IEEE DySPAN 2014 - SSPARC Workshop)

73. Tychogiorgos G, Gkelias A, Leung K (2011) A new distributed optimization framework for hybrid adhoc networks. In: GLOBECOM workshops
74. Shajaiah H, Abdelhadi A, Clancy C (2014) Spectrum sharing between public safety and commercial users in 4G-LTE. In: IEEE international conference on computing, networking and communications (ICNC)
75. Shajaiah H, Abdelhadi A, Clancy C (2013) Utility proportional fairness resource allocation with carrier aggregation in 4G-LTE. In: IEEE military communications conference (MILCOM)
76. Ghorbanzadeh M, Abdelhadi A, Clancy C (2014) A utility proportional fairness bandwidth allocation in radar-coexistent cellular networks. In: Military communications conference (MILCOM)
77. Khawar A, Abdel-Hadi A, Clancy TC (2014) Spectrum sharing between S-band radar and LTE cellular system: a spatial approach. In: 2014 IEEE international symposium on dynamic spectrum access networks: SSPARC workshop (IEEE DySPAN 2014 - SSPARC Workshop)
78. Ghorbanzadeh M, Abdelhadi A, Amanna A, Dwyer J, Clancy T (2015) Implementing an optimal rate allocation tuned to the user quality of experience. In: International conference on computing, networking and communications (ICNC), pp 292–297
79. Jiang T, Song L, Zhang Y (2010) Orthogonal frequency division multiple access fundamentals and applications. Auerbach Publications
80. Dohler M, Heath R, Lozano A, Papadias C, Valenzuela R (2011) Is the PHY layer dead? IEEE Commun Mag
81. Eldar Y, Merhav N (2004) A competitive minimax approach to robust estimation of random parameters. IEEE Trans Signal Process
82. Eriksson K, Shi S, Vucic N, Schubert M, Larsson E (2010) Globally optimal resource allocation for achieving maximum weighted sum rate. In: IEEE global communications conference
83. Ghorbanzadeh M, Chen Y, Clancy C (2013) Fine-grained end-to-end network model via vector quantization and hidden markov processes. In: IEEE conference on communications (ICC)
84. de Kerret P, Gesbert D (2012) Towards optimal csi allocation in multicell MIMO channels. In: Proceedings of IEEE international conference on communications
85. Shajaiah H, Abdelhadi A, Clancy TC (2014) A price selective centralized algorithm for resource allocation with carrier aggregation in LTE cellular networks. CoRR vol abs/1408.4151
86. Harks T (2005) Utility proportional fair bandwidth allocation: an optimization oriented approach. In: QoS-IP
87. Abdelhadi A, Clancy C (2014) Context-aware resource allocation in cellular networks. In: arXiv
88. Etkin R, Parekh A, Tse D (2010) Spectrum sharing for unlicensed bands. IEEE J Sel Areas Commun
89. Etkin R, Tse D, Wang H (2008) Gaussian interference channel capacity to within one bit. IIEEE Trans Inf Theory
90. Nandagopal T, Kim T, Gao X, Bharghavan V (2000) Achieving mac layer fairness in wireless packet networks. In: Proceedings of the 6th annual international conference on mobile computing and networking (Mobicom)
91. Dighe P, Mallik R, Jamuar S (2012) Analysis of transmit-receive diversity in Rayleigh fading. IEEE Trans Commun
92. Dighe P, Mallik R, Jamuar S (2005) On downlink beamforming with greedy user selection: performance analysis and a simple new algorithm. IEEE Trans Signal Process
93. Ghorbanzadeh M, Abdelhadi A, Clancy T (2014) A utility proportional fairness bandwidth allocation in radar-coexistent cellular networks. In: Military communications conference (MILCOM)
94. Erpek T, Abdelhadi A, Clancy C (2015) An optimal application-aware resource block scheduling in LTE. In: IEEE international conference on computing, networking and communications (ICNC) worshop CCS

95. Abdelhadi A, Clancy C (2015) An optimal resource allocation with joint carrier aggregation in 4g-lte. In: 2015 international conference on computing, networking and communications (ICNC), pp 138–142
96. NTIA (2010) An assessment of the near-term viability of accommodating wireless broadband systems in the 1675–1710 MHz, 1755–1780 MHz, 3500–3650 MHz, 4200–4220 MHz and 4380–4400 MHz bands. U.S, Department of Commerce
97. Abdelhadi A. Clancy TC (2015) Network MIMO with partial cooperation between radar and cellular systems. CoRR vol abs/1507.07267
98. Shajaiah H, Abdelhadi A, Clancy TC (2015) Robust resource allocation with joint carrier aggregation for multi-carrier cellular networks. CoRR vol abs/1503.08994
99. Shajaiah H, Abdelhadi A, Clancy TC (2015) An efficient multi-carrier resource allocation with user discrimination framework for 5g wireless systems. CoRR vol abs/1506.02448
100. Shajaiah H, Abdelhadi A, Clancy T (2013) Utility proportional fairness resource allocation with carrier aggregation in 4g-lte. In: IEEE military communications conference (MILCOM)
101. Shajaiah H, Abdelhadi A, Clancy T (2014) Multi-application resource allocation with users discrimination in cellular networks. In: IEEE international symposium on personal, indoor and mobile radio communications (PIMRC)
102. Shajaiah H, Abdelhadi A, Clancy T (2014) Spectrum sharing between public safety and commercial users in 4g-lte. In: IEEE international conference on computing, networking and communications (ICNC)
103. Lackpour A, Luddy M, Winters J (2011) Overview of interference mitigation techniques between wimax networks and ground based radar. In: Proceedings 20th annual wireless and optical communications conference
104. Sanders F, Carrol J, Sanders G, Sole R (2013) Effects of radar interference on LTE base station receiver performance. U.S. Dept. of Commerce, NTIA
105. Bjornson E (2011) Multiantenna cellular communications: channel estimation, feedback, and resource allocation. PhD thesis, KTH Royal Institute of Technology
106. Bjornson E, Bengtsson M, Ottersten B (2001) Receive combining vs. multistream multiplexing in multiuser mimo systems. In: Proceedings of IEEE Swedish-communication technologies workshop
107. Bjornson E, Bengtsson M, Ottersten B (2012) Areto characterization of the multicell mimo performance region with simple receivers. IEEE Trans Signal Process
108. Bjornson E, Bengtsson M, Ottersten B (2011) Computational framework for optimal robust beamforming in coordinated multicell systems. In: Proceedings of IEEE computational advance in multi-sensor adaptive processing
109. Bjornson E, Bengtsson M, Ottersten B (2011) Optimality properties, distributed strategies, and measurement-based evaluation of coordinated multicell ofdma transmission. IEEE Trans Signal Process
110. Bjornson E, Ottersten B (2010) A framework for training-based estimation in arbitrarily correlated Rician MIMO channels with Rician disturbance. IEEE Trans Signal Process
111. Bjornson E, Zakhour R, Gesbert D, Ottersten B (2010) Cooperative multicell precoding: rate region characterization and distributed strategies with instantaneous and statistical CSI. IEEE Trans Signal Process
112. Bjornson E, Zakhour R, Gesbert D, Ottersten B (2012) Optimal coordinated beamforming in the multicell downlink with transceiver impairments. In: IEEE global communication conference
113. Bjornson E, Zakhour R, Gesbert D, Ottersten B (2011) Characterization of convex and concave resource allocation problems in interference coupled wireless systems. IEEE Trans Signal Process
114. Boche H, Schubert M (2002) A general duality theory for uplink and downlink beamforming. In: IEEE vehicular technology conference
115. Boche H, Schubert M (2008) A calculus for log-convex interference functions. IEEE Trans Inf Theory

116. Bock F, Ebstein B (1964) Assignment of transmitter powers by linear programming. IEEE Trans Electromag Compat
117. Cai D, Quek T, Tan C, Low S (2012) Max-min SINR coordinated multipoint downlink transmission duality and algorithms. IEEE Trans Signal Process
118. Caire G, Jindal N, Kobayashi M, Ravindran N (2010) Multiuser MIMO achievable rates with downlink training and channel state feedback. IEEE Trans Inf Theory
119. Caire G, Ramprashad S, Papadopoulos H (2010) Rethinking network mimo: cost of csit, performance analysis, and architecture comparisons. IEEE Trans Inf Theory
120. Caire G, Shamai S (2003) On the achievable throughput of a multiantenna gaussian broadcast channel. IEEE Trans Inf Theory
121. Csiszar I, Korner J (1978) Broadcast channels with confidential messages. IEEE Trans Inf Theory
122. Dahrouj H, Yu W (2010) Coordinated beamforming for the multicell multiantenna wireless system. IEEE Trans Wirel Commun
123. Dardari D, Tralli V, Vaccari A (2000) A theoretical characterization of nonlinear distortion effects in OFDM systems. IEEE Trans Commun
124. Fan K (1953) Minimax theorems. Proc Natl Acad Soc
125. Farsakh C, Nossek J (1995) Channel allocation and downlink beamforming in an SDMA mobile radio system. In: IEEE international symposium on personal, indoor and mobile radio communications

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