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Moktan, Gautam Raj; Manner, Jukka

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Distributive Justice in Network Communications

Gautam Raj Moktan, Jukka Manner
firstname.lastname@aalto.fi

Comnet, Aalto University, Finland

Abstract: Communication networks often have limited resources to serve all users and flows, and therefore different network resource assignment schemes have been deployed that satisfy fairness notions such as max-min fairness or proportional fairness. The justification of why one notion suits over other must be given due analysis in designing and administrating of communication networks. We explore the development of such fairness notions and resource assignment policies from philosophical and economics roots and how they translate into network communications and its layered protocol architecture. We find that resource assignment policies are not commutative, which impacts communications traffic and its bidirectional nature. We observe the effect of prioritization in assigned resource amounts under different notions of the α-fairness spectrum and when the proportion of prioritized participants is varied. After an exploratory discourse, we formulate steps for designing and administrating resource allocation schemes for network communications that takes distributive justice into consideration.

Keywords: Networking, Fairness, Resource Allocation, Distributive Justice, Prioritization, Socio-Economics

1 Introduction

Design principles in resource assignment in network communications are guided by different objectives not only due to the plethora of services running on it but also due to the diversity of its stakeholders, administrative realms and constantly changing market forces. The need to understand the sources of the design principles has become even more crucial in today's Internet. There is no one-size-fits-all design in the way network resources are allocated to the applications running on it. Nevertheless, due analysis to the justification of why one notion suits over other should be included in the process of designing and administrating of communication networks. Tussles in cyberspace (Clark et al. 2002) result from inadequate design and self-interests of the users.

Resource assignment designs attempt to obtain efficiency and optimal usage of the resources. Fairness and distributive justice are quite important factors in designing network resource assignment schemes. There are various implementations of resource assignment schemes that satisfy fairness notions such as *max-min* fairness, *proportional* fairness and others. But such implementations fail to justify one particular notion over another in any particular implementation. This is due to the lack of regard to social factors and the subjective nature of fairness while developing resource assignment algorithms in communications networks. Justice and fairness are social concepts and knowing how it is conveyed in the networking world is important for anyone trying to develop resource assignment schemes in the context of communication networks.

In this paper, we highlight the translation of the commonly used fairness notions in communication networks resource assignment process to the broader philosophical concepts of social justice. We identify the different notions as belonging to different schools of justice principles. We explore the prevailing instruments of prioritization of individuals in the society for assignment of resources such as *price, lottery, first-come-first-served,* etc. By exploring a few resource assignment areas in communication networks and some prominent works of analysing fairness there, we follow our discussion by comparing and contrasting philosophical treatment of justice and fairness in society to that in the context of communications networks.

Network traffic traverse various resource assignment nodes cascaded along the network path. Such nodes of differing policies morph into an aggregated policy resulting into different assigned resource amounts, whose fairness notions are not explained by traditional notions. Such resulting notions are of significance in designing network algorithms and architecture as well as the creation of service level agreements (SLA) between different stakeholders of the networks. We find the policies under different notions not to hold commutative property, which is of importance considering the bidirectional nature of communications traffic.

To distinguish between prioritization and assignment, we analyse an example of short flow prioritizing policy. We observe the effect of prioritization in assigned resource amounts under different fairness notions of the α -fairness spectrum and also when the proportion of prioritized participants is varied.

We provide steps to be considered while designing resource assignment schemes in network communications to consider distributive justice. The article covers broader topics from disciplines of socio-economic sciences that delve into the matters of establishing fairness and justice in social groups and institutions while examining their application in the context of communication networks. Our hope is that this article highlights the importance of having the knowledge of distributive justice for the network architects, designers and administrator to implement appropriate systems. We begin in the next section by establishing the philosophical and socio-economical concepts relating to justice, resource allocation, distribution and societal welfare as background for the scope of our analysis.

2 Background Concepts

We briefly discuss few terms to familiarize the reader into the context of the paper. The terms stem from the field of philosophy and economics and help frame our analysis later.

Allocation vs. Distribution

We differentiate *allocation* and *distribution*. Allocation incorporates the purpose of the resources assignment, i.e. it considers division of resources among individuals whose desires and needs are known. Justification of division is easier in this case. Distribution however is less sensitive to each user and considers the problem of goods division in a group scenario. Justifying the fairness of division thus needs more effort. In this paper the term *'resource assignment'* is used to generically imply the division of resources among the participants in a manner agnostic to the allocation and distribution terms.

Distributive Justice

Normative Ethics prescribe the right way or ethical way to do things and there are three main disciplines under it. 1) *Deontological* position is that rightness of an action stems from its adherence to a rule or the motives behind it. While deontology indulges in actions that conform to one's duty and other's rights, 2) *Consequentialism* is about the results of such actions. Rightness of an action for a consequentialist depends on the outcome of such action. Many practical theories such as *Utilitarianism, Egoism, Welfarism,* etc. are developed from consequentialism. Another position in normative ethics is 3) *Virtue ethics* which places importance to the character of the performer of the action in determining the morality of the action.

Historically, the principles of distributive justice are normative principles designed to guide the assignment of the benefits and burdens of economic activity. Its scope varies on what is subject to distribution, the basis of the distribution and the nature of the subjects of the distribution (Lamont & Favor 2012).

There are several schools of thought regarding distributive justice derived from one or the other normative ethics positions. *Strict egalitarianism* states that in a just distribution policy, every person should have the same level of material goods and services no matter what. According to the *difference principle* (Rawls 2009), inequalities in distribution are allowed only when they are open to all under conditions of fair equality of opportunity and distributions should prioritize greatest benefit of the least advantaged members of society. This led Rawls to propose MAXI-MIN approach, i.e. maximize the opportunities and minimize the inequalities among all. *Welfare-based principles* prefer maximizing the overall level of wellbeing, which results in favour of majority. *Desert-based principles* focus on the entitlement to resource-share based on individual's toil. And *libertarian* principles do not require any distributive pattern to be termed just. Many policies in real world are derived from these principles per the justification of the people and the law of the land. Amendments are made in the policies and the best-suited ones are chosen for different contexts. We will attempt to map these principles to the schemes found in network communications in our discussion section.

Welfare vs. Entitlement

From a system viewpoint, we shall define welfare as the overall wellbeing of the system and entitlement as the shares of individuals in the system. To maximize it, welfare functions are built that incorporate different parameters depending on the context and the objective of the policy. At the same time, individuals' entitlements come into play and sometimes as opposing force. Individuals have different senses of entitlement depending of the justice principle they believe in. Sometimes referred to as individual rights and sometimes seen as selfishness, the perception of entitlement varies.

Awry sense of entitlement brings tension and instability in the distribution system. *Tragedy of the commons* (Hardin 2009) and the *price of anarchy* (system efficiency degradation) are the observed phenomenon in these situations. While utility is a perception and varies among individuals, welfare does not always satisfy the perceived entitlement of individuals. An equilibrium point is reached when these two forces interact. Resource assignment policies are expected to set satisfactory welfare in the system while avoiding envy among the individuals by satisfying their perceived entitlement or through justification for the inequality with compensation for such.

Social Indifference curves

Variation of utility and their relation to allocation policies can be demonstrated with the help of social welfare functions translated to social indifference curves as shown in **Error! Reference source not found.**. In the social indifference curve of pure utilitarian policy (on the left), different allocations are acceptable as long as the sum of derived utilities of the participants are the same. For a maxi-min distribution policy (on the right), while increasing the utility for one user, the utility for the second user, which has less utility, should not decrease.

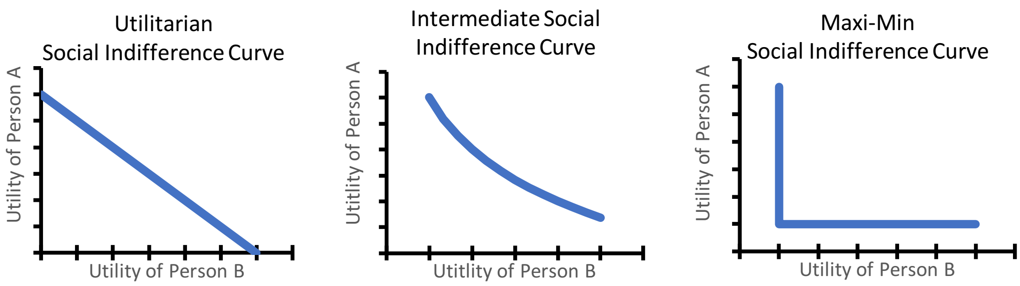

Figure 1. Different Social Indifference Curves

In most real-world cases, the intermediate indifference curves (in the middle) are applied which justify the increase in inequality by making the increased utility for one deriving more utility much greater than the decreased utility for the other. The two different curves in each sub-figure represent different total allocation capacities.

Efficiency and Fairness

Seminal works in the area of system efficiency and improvement come from Pareto, Kaldor and Hicks (Coleman 1979). A Pareto efficient system implies that one participant cannot benefit without causing loss to the other. If such optimality is not the case, then there exists room for Pareto improvement. Another view of system efficiency is provided by Kaldor-Hicks efficiency where the optimality is implied in cases where the loser of a contention can be compensated in some manner so that no one is worse off.

These measures do not consider the fairness provided by the applied policies. For example, given that 5 apples are to be shared among 5 people, a fair assignment is one where each person gets one apple. This is also Pareto efficient meaning that no one can get more apples without reducing another share. But another Pareto efficient assignment could also be such that one individual gets 5 apples and the remaining 4 get nothing. Despite being Pareto efficient, this is very unfair distribution. Thus, questions of fairness are put into the systems and policies under consideration independently of the efficiency and improvement factors.

Origins of Fairness

It is worthwhile questioning if fairness-seeking tendency is an inherent part of individuals developed through evolutionary process or is it inducted as a social construct. A study demonstrating capuchin monkeys rejecting unequal pay (Brosnan & De Waal 2003), hints that inequity aversion tendency results from evolutionary development of fairness seeking behaviour. While another study of contemporary small scale societies (Henrich et al. 2010) shows that notions of fairness increase steadily as societies achieve greater market integration thus linking fairness towards more of a social construct. However, one can observe in both scenarios, the visibility of division of goods has contributed to the generation of thoughts in test subjects in both experiments that morphed into fairness notions. This implies that fairness has an axiomatic relation to the perception of distribution and *"not only must justice be done; it must also be seen done"* (Kurka & Pitt 2016b).

Social Contract

The *social contract* (Hobbes 1928) stipulates that one consents to surrender some of his/her rights to the societal authority in exchange for the protection of the remaining rights. In communication networks, designers take away some of the justified share of resources in order to ensure remaining claims on the resources provided by the network. An example of this would be how QoS provisioning in the networks can discriminate between different traffic types according to their QoS classes.

Prioritization Mechanisms

In general practice, scarce resources are assigned to a group of participants in several ways (Parkin et al. 2008) which we refer to as instruments of assignment. These mechanisms are the ways to define the entitlement of the resource. In each mechanism, users are prioritized in the descending order of their possession of those criteria. (e.g. Priority can be set on the price the participant sets or the strength(force) the participant possess.)

- In the *market price* method, people who are willing and able to pay the price get the resource. This generally works well in competitive markets for most goods and services.
- A *command* mechanism has an authority that gets to decide who gets the resource. For systems where lines of authority are clear, and monitoring are easy, this method works well for delegating tasks.
- The *majority rule* is adopted and works relatively well when many participants are affected by the assignment.
- A *contest* can be used when the efforts of the participants are hard to monitor or control. The winner takes the resources in such contests.
- When the resources are given out sequentially and one at a time, *first-come, first-served* method works well.
- Sometimes randomly selected winners are given the resource through *lottery* when there is no way to easily distinguish which user of the resource would use it most effectively.

- Another mechanism is to provide resource to the preferred participant, which holds certain *personal characteristics*. An example would be to grant the resource to members with certain age or height.
- When *force* is considered the assignment scheme, participant with greater strength or skill obtains the resource from other participants.

Many of these methods also apply in communication systems in different forms. As a distributed system, implementing distributive justice in communication networks come with their own set of challenges (Kurka & Pitt 2016a; Stocker et al. 2017). Bandwidth, buffer space, processor cycles, battery life, frequency spectrum are some examples of the resource of economic values that are distributed among different entities and individuals. Mobile data packages with different pricing reflect the market price mechanism in action in communication networks. Much of the network functions and policies are delegated by network administrators, which show the command method of resource assignment. In wireless sensor networks, selecting cluster head done by collective decision making of nodes indicate a form of majority rule being used. FIFO (first-in-first-out) queues exemplify the First-come; first-served method while MAC layer random access demonstrates the lottery method. Quality of Service (QoS) provisioning based on flow types(Casoni et al. 2018; Hoßfeld et al. 2018) can be regarded as the personal characteristics based assignment instrument. Example of force in network communications would be the use of multiple Transmission Control Protocol (TCP) flows to attain more bandwidth share. Such instruments of allocation have been evolving in the communication networks along with Internet's evolution. Earlier networks generally used random access and FIFO mechanisms. As the network evolved, different assignment mechanisms were implemented such as pricing and QoS (Chikh & Lehsaini 2018).

Nevertheless, just distribution is required and fairness is called upon often (Ramanath et al. 2018) to scrutinize the resource assignment policies embodied by the prioritization and distribution mechanisms/instruments. The aforementioned different schools of distributive justice can view the justice and fairness of such instruments differently. Different metrics are used depending upon the context and with respective justifications. These policies define the architecture of the whole communication system and affect the services running on the system and the utility that the users obtain. Problems with implementing some of them are such that they add latency and computation into the networks, which often makes them unsuitable to implement. Some policies diverge from the foundation design goals of the system and some are too restrictive.

3. Resource allocation realms in network communications

We view the realms of resource allocation into two parts. The resource allocation policies are affected across the protocol stack by the code. They are also affected by the regulations enforced across the network path due to real space tussles.

3.1 Across the stack

Differences in the resources and administrative domains of each layer lead to different assignment policies in each layer of the stack. Processor time assignment was the first of the distribution policies to be implemented in computing. Time sharing systems were devised in the '50s that allowed multiple individuals and programs to share a common computing system. Since then, different policies developed to allow different priority levels to programs and individuals while balancing load and optimizing system utilization. Different kinds of formal scheduling methods are implemented for providing resource access to threads and processes. FIFO, SRT(shortest-remaining-time-first), fixed priority pre-emptive, round-robin, multilevel queue scheduling etc. are some of the available disciplines. Concurrency situations for input-output events led to the formulation of fairness notions based on the resource assignment for processing of threads and tasks. Fairness measures in scheduling stem from the basic property that asserts every thread that could make progress does, in fact, makes progress (Amsden & Fluet 2012).

Link layer: Media access is one vital resource for communicating entities to have. When multiple hosts are connected to a common medium, there are different methods about how each can gain its access without colliding with another host's transmission. CSMA (Carrier sense multiple access), Token Ring, ALOHA, TDMA (Time division multiple access), CDMA (Code division multiple access), FDMA (Frequency division multiple access), etc. are some of the available means to control which host gets to transmit through the medium at any given time and they also perform flow control (Kim & Yoon 2017). The transmission of data from a host is a non-deterministic process while the control mechanisms can be more concrete. The control mechanisms perform the resource assignment in these situations and fairness of such assignment is considered.

Network Layer and Routing: At the network layer of the TCP/IP stack, multiple paths are the resources and routing is the resource assignment mechanism. Different paths can be assigned to an incoming flow/commodity based on the bandwidth, network delay, hop count, path cost, load, MTU (maximum transmission unit), reliability, and communication cost of the forwarding path. Load balancing (Al-Najjar et al. 2017; Khan & Portmann 2017) is one of the objectives of the routers, which entails providing fair distribution of the path resource (considering all the path variables) to the flows.

Transport Layer: A heavily pursued topic in network communications is resource assignment and policy implementation at the transport layer(Sehati & Ghaderi 2016). The flow control(Teymoori et al. 2016), congestion control and multiplexing functionality of this layer have consequences in assigning network resources to the communicating hosts. Two distinct control mechanisms exist for such policy implementation. End-to-end mechanisms are available through congestion control algorithms, flow control and ports assignments while network mechanisms are available through buffer management, scheduling and queuing algorithms in the network nodes.

Application Layer: Resource assignment from application layer viewpoint arises from the specific requirements of applications and the traffic they generate. Some applications are delay sensitive, while others can be goodput (application level throughput) sensitive(Srinivasa 2017; Shameem et al. 2017). Traffic generated can be elastic (application can adjust to delay and throughput variations) or inelastic (such as streaming video). Though they depend on the lower layers to provide such guarantees, many mechanisms are being discussed for the fairness of web applications such as VoIP (voice over Internet protocol), peer to peer applications, first person shooter games, stock trading platforms, etc.

Modern day services operating in the cloud architectures pose various challenges of resource assignment, including access bandwidth, computing units, etc. Different algorithms are proposed as solutions to these problems as well (Wang & Jin 2016; Zalewski & Ogryczak 2016; Xu et al. 2016).

3.2. Across the network path

Network paths as a resource assignment realm imply heterogeneity of the networks due to their administrative boundaries (institutional policies, national policies, etc.) and financial considerations (SLAs). These factors affect the resource assignment policies in place (Noormohammadpour & Raghavendra 2017) and accordingly users derive some notions of fairness from them. In fact, ordinary end users comprehend such notions of fairness more easily than the ones resulting from policies implemented in the stack. Juxtaposing different assignment schemes across the layers give a cascaded output that might not be the same as the anticipated overall policy for the network. Different amounts can be the resulting assignment to the end users when the network communication flows go through these modular forms of independent schemes.

4. Formalizing Fairness in Communication Networks

Fairness implications of channel scheduling was studied as early as 1982 (Wong et al. 1982) and still various issues are being analysed in different resource assignment realms of routing(Kumar et al. 2018), congestion control(Low 2017) and buffer management(He & Lin 2017) to improve fairness of the resource assignments.

A 1990 survey (Varshney & Surajit 1990) classifies fairness notions in computer networks according to *Fair resource allocation*, *Equal performance*, and *Balanced interference among users*. They also state that people have varying preferences thus, network managers have different perspective and goals than users, making resource assignment a hard problem to solve.

One research (Mark 1985) defines fairness as the ability to provide equal satisfaction to all users while another (Jaffe 1981) states that a network is said to be fairly utilized if the total network throughput is maximized subject to the constraint that the network capacity is fairly distributed among all the users. Douligeris and Kumar (Douligeris & Kumar 1995) identify the fairness control mechanisms for inter-networking as bandwidth assignment and buffer management while that of intra-networking as delay and throughput concerns. They list several criterions of fairness for each realm. They define fairness as the quality of a network when specified objectives are met without violating the administrative concerns, subject to the network constraints while preserving the independence factors for every user.

Denda et. al. (Denda et al. 2000) observed that the concept of maximized welfare in political science corresponds to the commonly used definition of fairness in computer networks. In their imitation of Maslow's pyramid for communication network users, fairness is at the highest level. On providing solution to the fairness problem, they note that any algorithm that solves the cake division problem (i.e. all participants believe they got a fair share) requires active participation of the cake eaters. In communication networks, it is not feasible due to scalability reasons. They provide various welfare functions to correspond to various resource allocation measures and designate two classes of fairness in communication systems. Macro fairness is the traditional notion of fairness from network point of view while Micro fairness would imply fairness in the distribution of service parameters that are important to different application needs. They note *'Fair delay management, fair loss rate distribution, and fair jitter control have hardly been addressed at all levels of abstraction, which, in our opinion, is insufficient for future applications with fairness requirements.'*

For networks with quality of service guarantee, the fairness criteria will be different from that of the best effort networks with even QoE fairness being prioritised in present day services (Hobfeld et al. 2017). Due to bandwidth reservation and call admission control, blocking probability becomes a more important fairness measure. Hwang et. al. studied the fairness problem in bandwidth guaranteed networks by concentrating on the impact of call admission policies on the fairness measure under homogeneous network (Hwang & Chi 2003). They proposed a fairness measure based on the blocking probability and proposed five call admission policies; Complete Sharing Policy, Complete Partitioning Policy, Trunk Reservation Policy, Look Around Policy and Blocking Balancing Policy.

One can also take a vector approach to resource assignment as Kumar and Klienberg (Kumar & Kleinberg 2000) where, assigned amounts are viewed as vectors and coordinates represent each individual. Their method could formulate solutions to the issues of bandwidth assignment, scheduling and facility location based on objectives of fairness notions prescribed as vectors. Another work on Fairness(Nilsson 2006) used preference relation tools to demonstrate the concept of one vector being more fair than another. It indulges mostly in backbone networks where a user implies a bundled set of flows and resource assignment solution constitute of admission control techniques. It reinforces the understanding that to obtain a fair solution, one must relax the requirement of a high total throughput and vice versa.

Chiu et. al. explore the impact of inelastic flow's traffic controls on fairness (Chiu & Tam 2007). Since, subjecting inelastic flows to fairness congestion control on a per-flow basis does not necessarily maximize the networks utility, inelastic flows may follow their own form of traffic control, such as admission control (without congestion control) which is by definition unfair in the traditional sense. They state that in a self- regulated network, it is still sensible to apply TCP- friendliness principles at the aggregate level than at per-flow level to maximize social welfare. Also, some TCP-friendly admission control, when applied to inelastic flows, out-performs TCP-friendly congestion control in terms of both elastic as well as inelastic throughput.

4.1. Fairness Measures

Quantifying the fairness of an assignment is very helpful for evaluating different policies. In networking area, Jain's fairness index (Jain et al. 1984) has been the de-facto standard. For n users and X_i share allocated to each, it is calculated as:

$$J(X) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n.\sum_{i=1}^{n} X_i^2} \quad (1)$$

The problem with this index is that for totally unfair case, $J(X) \neq 0$ because for example if all resource is given to 1 individual out of n contenders, the index becomes $\frac{1}{n}$ while it should have been zero.

A new fairness function is provided by Zhenmin Chen (Chen & Zhang 2005) adding improvement to Jain's model in totally unfair cases while a later work provides fairness function to account for multiple priority levels (Chen & Zhang 2010). Sally Floyd has gathered other measures of fairness between flows such as the product measure and Epsilon fairness in RFC 5166 (Floyd 2008). Apart from these indices, GiNi index and other measures of statistical dispersion such as entropy can also be used to infer the fairness of distribution of goods.

For flows with different resource requirements there are concepts of max-min fairness, proportional fairness and minimum potential delay fairness. These concepts are to be considered in case of the communications networking environment.

Max-Min: The operating principle of this resource assignment scheme (Demers et al. 1989) is to maximize the minimum data rate any flow achieves and then to maximize the second lowest data rate a flow achieves and so on. The fair queuing algorithm and the round robin (in case of equally sized packets) achieve max-min fairness.

Maximum Throughput Resource Management: This scheme prioritizes capacity allocation to the least expensive flows. This makes sense in wireless scenarios where the difference in cost of flows are significant. As setback, this can starve the expensive flows. *Fairly Shared Spectrum Efficiency* is the measure for spectrum utilization in such cases.

Proportional Fairness: Proportional fairness (Kelly et al. 1998) attempts to allocate resources in such a manner that while trying to maximize the network throughput, expensive flows do not suffer starvation. A minimum service is given to all flows. Expensive flows obtain a lower service quality after the minimum service level. By definition, proportional fair allocation states that the aggregate proportional change in any user's allocation should be zero or negative. i.e. if C is to be distributed among n participants with x_i being user i's share, then proportional fairness ensures:

$$x_i \geq 0, \tag{2}$$

$$\sum_{i=1}^{n} x_i \leq C \; and \tag{3}$$

$$\sum_{i=1}^{n} \frac{x_i^* - x_i}{x_i} \leq 0 \tag{4}$$

α *- fairness:* Mo and Walrand's α - fairness (Mo & Walrand 2000) generalizes proportional fairness and can also come to be approximately close to max-min fairness depending upon different values of α , specifically $\alpha = 1$ and $\alpha \rightarrow \infty$. They state an allocation to be (p, α)-proportional fair with $p = p_1, \ldots, p_N$ and α being positive numbers when:

$$x_i \geq 0, \tag{5}$$

$$\sum_{i=1}^{n} x_i \leq C \; \; and, \tag{6}$$

$$\sum_i p_i \frac{x_i - x_i^*}{x_i^{*\alpha}} \leq 0 \qquad (7)$$

They also describe a utility function that satisfies such notion as:

$$U_i(x_i) = \frac{x_i^{1-\alpha}}{1-\alpha} \qquad (8)$$

Axiomatic approach: Based on five axioms, namely of *Continuity, Homogeneity, Saturation, Partition and Starvation* (Lan et al. 2010), Tian's model of fairness captures multiple notions of fairness and fairness indexes. Their resulting generalized fairness measure is:

$$f_\beta(X) = sign(1-\beta)\left[\sum_{i=1}^{n}\left(\frac{x_i}{\sum_j x_j}\right)^{1-\beta}\right]^{\frac{1}{\beta}} \qquad (9)$$

Different values of β turn this fairness measure into previously mentioned measures. e.g $\beta \rightarrow \infty$ implies entropy fairness, $\beta = -1$ leads to the Jain's index and $\beta >= 0$ gives one component of the α-fair utility function. From another perspective, one can see this measure unifying both the index based approaches and utility based approaches of fairness with the corresponding values of $\beta < 1$ and $\beta >= 0$. Details can be found in (Lan et al. 2010). An interesting property of this measure is that one can reverse engineer the notion of fairness held by a participant as a certain value of β by subjecting them to view different allocations and make judgements.

Huaizhou Shi et. al. (Shi et al. 2014) have done a comprehensive survey on the major works done about fairness issues in networks. They also propose a fairness management framework as a (Plan-Do-Check-Act) PDCA loop. Our guidelines in this paper are on a more macro scale than the PDCA Approach. But first we start our discussion in the next section with the examination of developed fairness notions in networking from socio-philosophic sense.

5. Discussions

So far we discussed the need to consider fairness and distributive justice in computer networks and put forth the principles of resource allocation and distributive justice. Much work has been done to formalize the notion of fairness in communication systems. Different measures of fairness exist to evaluate the justice provided by any given distribution policy. Amid these background materials we can discuss how schemes are to be formulated and for what ends such means work towards.

One can easily observe that given the numerous methods of assignment, notions of fairness, measures of evaluating such assignment, realms of implementation, multi-party involvement and the subjective nature of utility of resources to a user, it is a complex task to design policies of assigning resources. Many factors need to be considered to provide a satisfactory level of service, which imparts no envy among the participants.

Satisfying user needs lie on one side, efficiency is sought by the network operators for full utilization of their infrastructures and the trade-off of these two (Yang et al. 2018; Zabini et al. 2017) need to maximize overall social welfare as is the objective of authority bodies. Decoupling the preferences of these three parties help in getting a clearer picture while a holistic view should be kept simultaneously to monitor the stability and equilibrium when these forces interact.

We can say that the *maximum throughput resource management* scheme is a *utilitarian* model applied in network communications as it asks to maximize the overall utility of the system even at the cost of depriving some of the participants. The notion of fairness it claims would not be universal, as the deprived participants would definitely call it unfair.

The *max-min* model of resource assignment in communication networks, which is a *deontological* perspective carries with it the justice virtue theorized by the Rawlsian *difference principle* and his MAXI-MIN rule. Like MAXI-MIN, max-min attempts to maximize the resource assigned to the flow that has the least amount assigned. In this regards, the justice as fairness is to be achieved even at the cost of system efficiency.

Proportional fairness is then a compromise between the two models where in conditions are set for justifying the inequality of the resource assignment process. Various weights are put into the proportional fairness model to attribute for the conditions. These three approaches can be then fitted into the indifference curves of **Error! Reference source not found.** to explain that the intermediate indifference curves represent proportional fairness.

It also begs the question of what is being traded off while designing resource assignment schemes with proportional fairness scheme. The *price of fairness* can be quantified from comparing the allocation schemes. If one were to derive the loss of Rawlsian justice by deviating from the utilitarian model, the ratio of utility loss from a particular allocation scheme to that of total utility in a pure utilitarian scheme provides the price paid. On other end, from a Rawlsian perspective, justice is being traded off to achieve better overall utility of the system. One can relate this to the *social contract* wherein designers take away some of the participants claim in absolutely justified share of resource in order to ensure remaining claims on the resources provided by the network.

Specific to the computer-networking context where layered protocol stack interact, resource distribution mechanism can be different at the different layers. Their designs are driven with different objectives, some for efficient use of wireless spectrum, some for providing reliable data transfer, some for providing secure transport and some for best-effort transport. These manifest in differing distributive policies of each implementation.

When the design considers the user's desire and needs by formulating utility functions, we tend to move towards *allocation* principles but it is more evident when weights are given to users to set the priority for the allocation. Thus, designers need to be aware of the effect of weights in their conception of fairness notion and the resulting assignment policy. The following subsection clarifies this through the α-fairness and the effect on Jain's index of the resulting distribution.

5.1. Prioritization under various α-fairness notions

The utility function for α-fairness is given by equation 8. Then the distribution problem is a constrained optimization problem to maximize the sum of the utilities. We formulated a scenario and used CVXPY solver (Diamond & Boyd 2016) to obtain the resulting distribution for this problem.

We considered 100 units of resources to be assigned to two users, *User1* and *User2*. While keeping weights p_i for *User1* constant at 1 ($p_1 = 1$), weight for *User2* was varied from 1 to 20, ($p_2 = [1 \dots 20]$). Using CVXPY, the resulting resource assignments x_i of the two users (specifically x_1 and x_2) under different α -fairness notions are shown in **Error! Reference source not found.**.

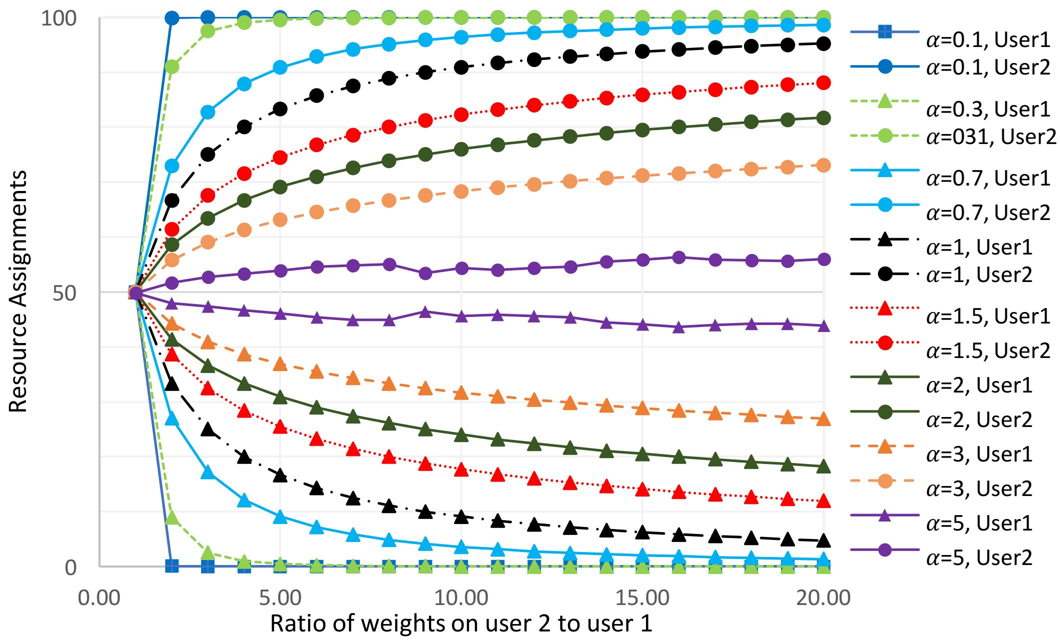

Figure 2. Different α-values react differently to weights variation

We can observe that under the same weights i.e. 1, all fairness notions assign equal value of 50 to each user. As the weights increase, under smaller values of α, the resources are assigned fully to the weighted users. While for bigger values of α the weights have less impact on the assignment of resources. This paints a picture on the relationship of fairness notions and the treatment to the prioritized participants of a resource assignment process.

5.2. Prioritizing short flows

The variation in traffic flow-lengths in communication networks has led to discussions on flow-length based utilities. There are significantly more short flows in networks than long flows and they also hold more utility per unit length in general (Moktan et al. 2014). Prioritizing short flows also provides benefits such as energy efficiency and improved user experience. There have been various proposals for enabling such prioritization (Chen & Heidemann 2003; Moktan et al. 2012; Rai et al. 2005; Briscoe et al. 2016). Often the fairness of such scenario is questioned that if short flows are given more priority, there will be more short flows and long flows will be eventually starved. We test this scenario by varying the proportion of short and long flows in different weight settings.

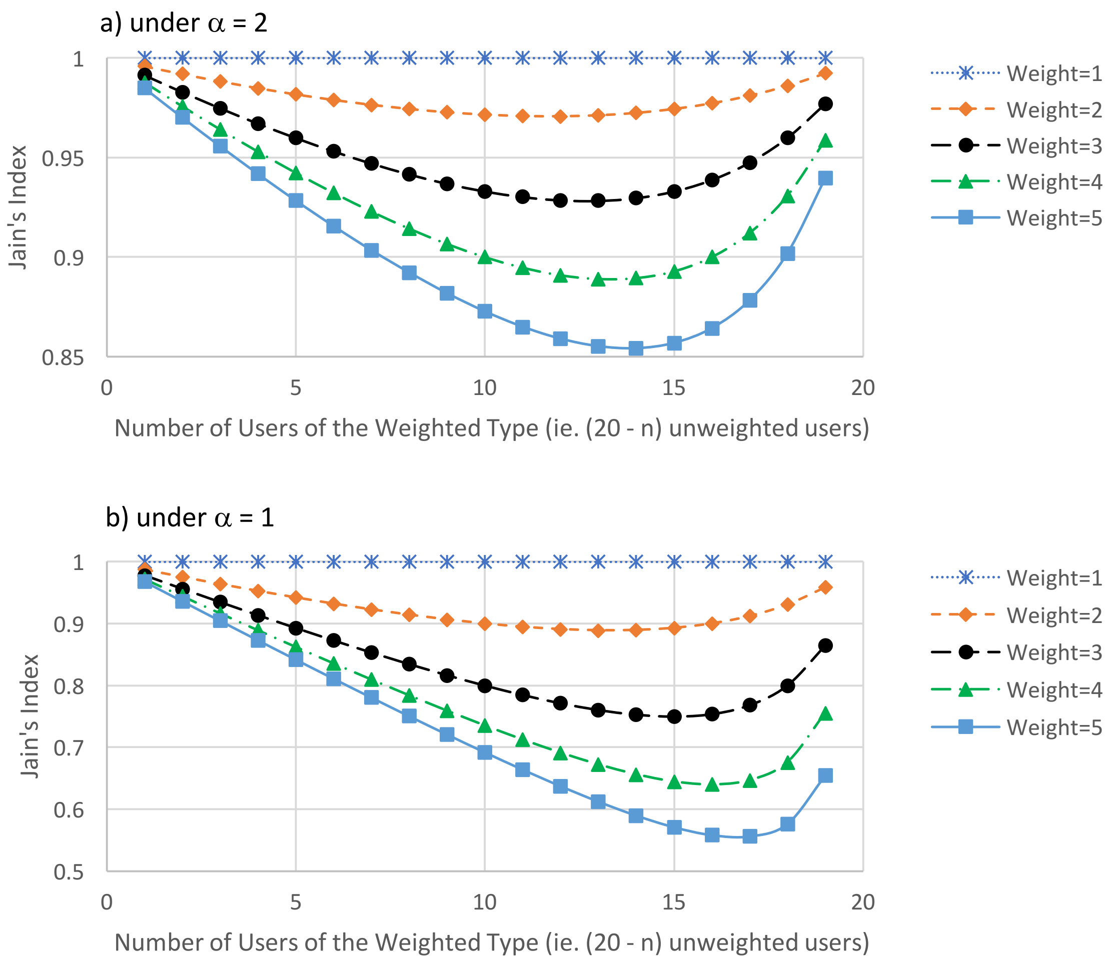

Figure 3. Jain's index under different proportions of weighted flow types

In terms of the α-fairness notion, $\alpha = 2$ is termed minimum-delay-throughput-management scheme and it turns the weighted α-fairness utility function into:

$$U_i(x_i) = -p_i \frac{1}{x_i} \tag{10}$$

If the flow utility is related to the delay of the flow (which is proportional to the flow completion time) and the resource assignment problem is to minimize the delay for flows, prioritizing short flows implies that short flows are assigned higher weights so that they get more resources leading to lesser delay than the long flows. The resources are then assigned according to varying weights as depicted in the earlier **Error! Reference source not found.** for $\alpha = 2$.

In our test scenario, 2000 units of resource are to be assigned among 20 users. Users are either short or long flows and proportion of each is varied from 1-20. The short flows are given varying weights compared to long flows and the results are in **Error! Reference source not found.** where we conduct the same test for the case $\alpha = 1$ (for the commonly used log utility function).

We observe that for same weight (i.e. no discrimination), the resulting assignment has obvious Jain's index of 1 for all proportions in the mix. As the weights to prioritized flows increase, the least value of Jain's index is not at the intuitive middle where each 10 users are short and 10 users are long but rather at a point where there are a larger number of weighted users. It implies that as more weights are put to a user type, the inequality increases with the proportion of that user type. Observing the difference between **Error! Reference source not found.** (a) and (b), the severity of inequality under α =1 is more prominent than under $\alpha = 2$.

Considering the prioritization of short flows using the case $\alpha = 2$, **Error! Reference source not found.** (a) shows possibility for one to assign appropriate weights to implement such short flows favouring policies with the knowledge of proportions of user types and tolerable levels of Jain's index values.

5.3. Cascading Policies

Different policies are implemented at different realms in the network stack and communication path. And for participating communication flows, the cascading effect of such various policies can result quite differently than originally envisioned. We show below experimentally how such assignment occurs along the network path and has the non-commutative property.

Table 1. Cascade matrix of different $\boldsymbol{\alpha}$ values and corresponding assignments and Jain's indices

		α1						
		0.2	**0.5**	**1**	**1.5**	**2**	**5**	**10**
α2	**0.2**	(0.307,9.692) **0.532**	(0.615,9.385) **0.565**	(0.615,9.385) **0.565**	(0.615,9.385) **0.565**	(0.615,9.385) **0.565**	(0.615,9.385) **0.565**	(0.615,9.385) **0.565**
	0.5	(0.307,9.692) **0.532**	(2.009,7.99) **0.737**	(3.34,6.66) **0.901**	(3.869,6.13) **0.951**	(4.019,5.981) **0.963**	(4.019,5.981) **0.963**	(4.019,5.981) **0.963**
	1	(0.307,9.692) **0.532**	(2.009,7.99) **0.737**	(3.34,6.66) **0.901**	(3.869,6.13) **0.951**	(4.146,5.854) **0.972**	(4.655,5.344) **0.995**	(4.827,5.172) **0.999**
	1.5	(0.307,9.692) **0.532**	(2.009,7.99) **0.737**	(3.34,6.66) **0.901**	(3.869,6.13) **0.951**	(4.146,5.854) **0.972**	(4.655,5.344) **0.995**	(4.827,5.172) **0.999**
	2	(0.307,9.692) **0.532**	(2.009,7.99) **0.737**	(3.34,6.66) **0.901**	(3.869,6.13) **0.951**	(4.146,5.854) **0.972**	(4.655,5.344) **0.995**	(4.827,5.172) **0.999**
	5	(0.307,9.692) **0.532**	(2.009,7.99) **0.737**	(3.34,6.66) **0.901**	(3.869,6.13) **0.951**	(4.146,5.854) **0.972**	(4.655,5.344) **0.995**	(4.827,5.172) **0.999**
	10	(0.307,9.692)	(2.009,7.99)	(3.34,6.66)	(3.869,6.13)	(4.146,5.854)	(4.655,5.344)	(4.827,5.172)

		0.532	0.737	0.901	0.951	0.972	0.995	0.999

In order to perceive the effect of cascading policies, we consider a system with two nodes (X and Y) with different policies ($\alpha1$ and $\alpha2$) as in **Error! Reference source not found.**. The users A and B are weighted differently. We consider two distinct fairness notions $\alpha = 1$ and $\alpha = 2$, i.e. The respective utility functions are:

$$U_i(x_i) = p_i \log(x_i) \; and \quad (11)$$

$$U_i(x_i) = -p_i \frac{1}{x_i} \quad (12)$$

The policies at each node then attempt to maximize these utility functions for the participants.

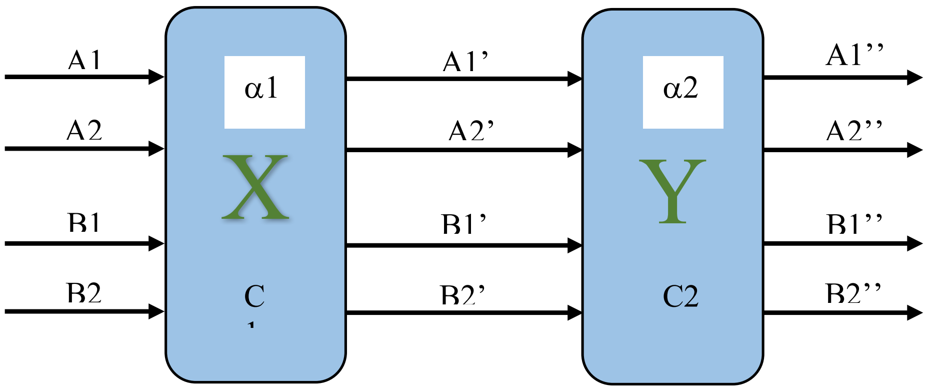

Figure 4. Cascade of fairness policies

We experiment the proposition above with different values of α by running those values with CVXPY solver. We consider the above system (as in **Error! Reference source not found.**) with 20 participants, 10 of each type (A and B). The fairness policies (i.e. α values) in the nodes are varied from 0.2 to 10 as shown in Table 1. The capacity constraints of nodes X and Y are fixed at $C1 = 200$ and $C2 = 100$ resource units respectively. And the weights for User type B are twice that of user type A at each node. We observe the effects of an assignment policy to the participants. The CVXPY solves the optimisation problem and gives an allocation vector for the 20 users. The resulting amount of resource assigned to each type of user as well as the corresponding Jain's index are tabulated in Table 1. For example, for $\alpha1 = 0.2$ and $\alpha2 = 0.2$, the 200 resources are assigned among the 20 users, 10 of each type so that each user of type A gets 0.307 and each user of type B gets 9.692 units of resource and the resulting Jain's index of this assignment is 0.532.

We see from the table that for $\alpha1 = 2$ and $\alpha2 = 1$, the Jain's index is 0.9 and when switching only the alpha values (fairness notion) in the nodes we get the Jain's index for $\alpha 1 = 1$ and $\alpha 2 = 2$ is 0.971. In general, we see that $J_{ij} \neq J_{ji}$. The inequality of final assignment when we switch the placement of the policies only reveals that distributive policies (i.e. fairness notions) do not hold commutative property. This has significant issues in creating policies for the networks as network traffic have bidirectional property.

Another interesting aspect is the fact that we see that $\alpha 2$ is mostly dominant in determining the resulting assignment. Since node Y has less capacity, it becomes the bottleneck and the policy applied there i.e. $\alpha 2$ is dominant in determining how much resource is assigned to each traffic flow. In particular, for all values of $\alpha 1 > 1$, the resulting assignment depends only on the value of $\alpha 2$. i.e. the fairness policy of the bottleneck is determinant in resulting assignment. But for values of $\alpha 1 < 1$, this is not true. For $\alpha 1 = 0.2$, the inequality persists even for higher values if $\alpha 2$. This is because node X's policy has heavily biased towards weighted flows already. Depending on the different values of $\alpha 1$ and $\alpha 2$, dominance of the effect of each node in resulting assignment varies.

To highlight the manifestation of the cascading policies in communication network, consider two users U1 and U2 video conferencing with each other over the network through their mobile phones. Consider U1 has 4G and U2 has 3G. The video traffic from U1 faces the resource allocation realm at his first hop where the 4G base station allocates data rate according to proportional fairness policy $\alpha = 1$. Then the traffic encounters various queues and schedulers through its path where max-min fairness policy $\alpha \to \infty$ dictates how much rate it gets assigned. And again, at the last hop, the 3G network assigns resources according to proportional fairness policy. The reverse flow from U2 to U1 also goes through similar nodes with different polices. And now we can see that the resulting resource assignments for the forward and reverse flows encounter differing treatments by the network by the virtue of how the policies are cascaded along the path and their respective bottleneck capacities.

Traffic shaping policies and resource assignment policies are applied in the network nodes using various notions of fairness. But upstream and downstream flows can obtain different assignment of resources according to the arrangement order of policy nodes and their notions of fairness. Also, the upstream and downstream of the same communication flow can hold different weights, which can further affect the resulting assignment. These factors and their effect should be made available to the network designers and policy enforcers to ensure that the intended results are obtained in resource assignment processes. Developing an analysis framework in this area could very helpful in gaining insight on how networks actually treat flows.

6. Design guidelines on distributive justice

We attempt to provide pointers for network architects, designers and administrators (Cath & Floridi 2017) while considering the distributive justice provided by communication infrastructures. These are the considerations for design of resource allocation schemes.

Primary needs first: Basic connectivity, security, robustness, etc. are most crucial aspects for the network. For ordinary users, it is difficult to perceive the assignment policy without specific evaluation tools. But distributive justice will eventually be called upon after those needs are met, thus considering resource allocation policies and the fairness measures alongside will help build foresight.

Entities and utility: Participants of the assignment procedure do matter. Applications have varying needs and network regimes have varying constraints. Private and public networks operate with their own agreed values that guide the assignment policy while they cumulatively affect the end-to-end service outcome. Peering relationships between networks affect the allocation framework significantly. Equal is not always fair. Different entities have different resource requirements and the derived utilities differ depending on many factors. Thus, policies must consider such requirements.

Selection of Metric: Proper metric selection is significant in assigning resources. Network parameters provide varying utilities to participants. Fairness of assignment is associated with each parameter. For example, TCP friendliness concerns with providing flow-rate fairness. Briscoe's argument (Briscoe 2007) on fairness mechanisms derived from the cost of a user's action to others leads to a different sort of metric formulation. Taking bytes instead of packets to design congestion management schemes have been proposed(Briscoe & Manner 2014). Thus, different metrics can be used while justifying fairness of distribution and they will have consequent impact on the service resulting from the policy.

Setting appropriate weights: We highlighted the significance of weights to prioritize participants of resource assignment policy. Weights can lead to unequal assignment of resources under fairness notions. Appropriateness of weights can be a different problem of its own depending on the context of resource assignment. It is best if suitable parameters can be selected that act as weights automatically for the participating individuals.

Trade-off exists: An unrestrained optimization of energy efficiency leads to extreme throughput unfairness. Attempting thorough inspection of the participating entities require heavy computation. Thus, juggling between fairness, efficient utilization and overall welfare to obtain a balanced and stable trade-off is the key.

Contradicting policies: One should be aware of contradicting policies and the resulting situation. Random access provides certain kind of distribution policy while priority-based access provides a different kind. If they are cascaded in the different layers or through different middle-boxes it morphs into quite different overall policy.

Fair Rules Vs. Fair Results: Two contrasting perceptions come into play in this regards: 'It is not fair if the result is not fair' vs. 'It is not fair if the rules are not fair'. Not everyone is fair minded and/or with similar capabilities and/or at the same starting level, thus fair rules might not lead to fair result. While on the other hand, ensuring fair result will require more effort and authoritative policies. To deploy such rules they have to be fast as well (Tsioliaridou et al. 2017).

Following these steps to design and administer communication networks will help improve the distributive justice provided by the network. The objective of resource allocation in communication networks is a moving target but one can come closer to satisfying the fairness needs with due consideration to the different aspects, involved parameters and informed contextual judgment.

6. Summary and Conclusion

In this paper, we emphasized on the significance of a clearer formulation of distributive justice policies and mechanisms to be implemented in communication networks. We formed the philosophical background for the origins of justice and fairness and contrasted the resource assignment mechanisms in practice in many economic activities to that of communication networks. We described the different realms in the network where resources assignment problems occur. We explored how fairness is characterized in communication systems as well as different measures created to quantify them. We experimented on the effect of weights on different notions of fairness as well as the effect of proportion of weighted participants to the resulting assignment. We demonstrated that cascaded policies can have an unanticipated effect in the aggregated resource assignment and that the policies are not commutative. Finally, we prescribed rough guidelines to be considered while making judgments about resource assignment policies and their implementation.

Much work can be done in this area to translate justified resource assignment in communication networks. The interaction among various fairness notions has been raised in this paper, which needs to be further examined to develop generic frameworks. Standards for formulating prioritization process can be developed for various scenarios, which would be very helpful in creating the envisioned framework. The temporal aspect of fairness can also be linked to the distributive justice process. Being unfair for a short time but fair in the long run can be explored to develop various novel algorithms. Various resource prioritization schemes allow users to make their own strategy in competing for the resources and Nash equilibrium based fairness notions are used to study such processes. The questions addressed in this paper can be tackled under such notion of fairness too.

Conflict of interest disclosure

*The authors declare that there is no conflict of interest regarding the publication of this paper.

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