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Abstract: Fairness in multihop ad hoc networks has received considerable attention in the literature. A plethora of protocols have been proposed, which compute the "optimal" bit rates of the transmitting mobile nodes over short time-scales so that a certain fairness criterion is met. However, there has been limited research on the impact of the varying short-term allocations of these protocols due to nodes mobility on the user-perceived QoS (and social welfare) for services of long duration. In this paper, we introduce a utility-based framework, based on *QoS-aware history-dependent* utility functions. These functions quantify the satisfaction that the users of the MANETs obtain from the way their long-lived service sessions are allocated bandwidth, due to the behavior of the fairness protocols proposed for ad hoc networks. Finally, we demonstrate the framework's usefulness, by performing a comparative assessment of the fairness protocol of [19] with the standard IEEE 802.11.

Key-words: Ad hoc, fairness, history-dependent utility function, MANET, QoS, social welfare

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Des fonctions d'utilité pour évaluer l'équité dans les réseaux ad-hoc

Résumé : On peut trouver une littérature considérable à propos de l'équité dans les réseaux ad hoc multi-sauts. Les nombreux protocoles qui ont été proposés déterminent les débits "optimaux" pour les nœuds émetteurs sur de courtes échelles de temps selon un certain critère d'équité. En revanche, l'impact des variations à court terme de ces allocations dues aux déplacements des nœuds sur la qualité de service perçue par l'utilisateur pour des services de longue durée a fait l'objet de peu de recherches. Dans ce rapport, nous proposons un cadre d'évaluation s'appuyant sur des fonctions d'utilité à mémoire. Ces fonctions quantifient la satisfaction des utilisateurs selon la manière dont évolue la bande passante que le réseau leur alloue, et donc le comportement des protocoles des réseaux sans-fil sous-jacents. Enfin, nous utilisons ce cadre en comparant le standard IEEE 802.11 avec le protocole équitable de [19].

Mots-clés : Ad hoc, Equité, fonctions d'utilité m'emoire, MANET, QoS, choix social

1 Introduction

Mobile ad hoc networks (MANETs) are wireless, self-configuring networks of mobile nodes, the union of which form arbitrary topology. The nodes that also serve as routers are free to move arbitrarily; thus, the network's topology may change rapidly and unpredictably. MANETs can be used by their nodes to exchange content or acquire Internet access via the dynamic network topology. Due to its simplicity and its commercial availability, most of these networks are based on the underlying wireless technology IEEE 802.11. Some works have shown that this use raises issues in terms of efficiency and fairness [5]. Different protocols that attempt to improve the unfair way that the various flows are allocated bandwidth in the standard IEEE 802.11 protocol have been proposed (see for instance [2, 16, 19, 23]). Most of these studies evaluate the performance of the proposed solutions on a short time scale: each scenario is evaluated under a given topology (that can be a random one) with fixed pairs communicating according to a given traffic. These evaluations validate or not the effectiveness of the bandwidth allocations on a short time scale, i.e. they show if flows penalized in some configurations have their throughput increased or not. Henceforth, these allocations are called instantaneous bandwidth allocations. But in a long time period, traffic patterns may vary, also due to the nodes mobility. Therefore, it is very likely that flows, penalized under a configuration during a given time period, do not encounter any fairness issues during the remaining time.

Therefore, we think it is meaningful to perform a higher-level evaluation of the ad hoc fairness schemes. This evaluation should be economic-aware, that is it should reflect the economic value of the long-duration service sessions. This value is well defined for the services, as opposed to that of the uncorrelated "utilities" computed over the instantaneous rates allocated. Also, users only care about their service QoS, while they are indifferent towards the underlying network protocols and fairness schemes. These issues motivate the use of utility functions, which can serve as a common ground of comparison of the various fairness schemes whose maximization goals are inherently different (e.g. max-min fairness, proportional fairness etc.). In this paper, we propose a utility-based framework for the assessment of the performance of MANETs under various fairness schemes, which relies on the definition of QoS-aware history-dependent utility functions pertaining to the various services.

The remainder of this paper is organized as follows: In Section 2, we briefly overview related work and introduce our utility-based framework. Section 3 contains a classification of user services with respect to their sensitivity to various QoS parameters. In Section 4, we define utility functions for the services of these classes. In the penultimate section of the paper, we apply the proposed framework to comparatively assess the performance of the fairness scheme of [19] with that of standard IEEE 802.11 and provide some experimental results thereof. Section 6 contains directions of future research and some concluding remarks.

2 Related work and our approach

Since the seminal work of John von Neumann and Oscar Morgenstern [20], utility functions have been extensively used in economics, decision-making, game theory, grid and computing systems (refer to [6], [18] [21] and references therein). There have been some research efforts to use utility functions in order to measure user satisfaction in wireless networks [15], [17], [13], [11]. The utility functions used in these works, depicted as Figure1, quantify the benefit that users obtain from being allocated a certain bit rate in very short time scales. These benefit values are not correlated and thus neglect the severe impact of important QoS parameters, such as delay, on the user-perceived QoS for the service of long duration. Finally, there are also studies on the impact of fairness schemes on the network performance, however no association with users' utility is performed [10], [3], [12]. Therefore, we believe that assessing the impact of the various ad hoc fairness schemes upon the resulting user-perceived QoS and the social welfare attained is both of high importance and an open research issue.

QoS-aware history-dependent utility functions are an extension of standard utility functions for expressing the value attained over a long time scale from receiving various levels of QoS at short time scales, henceforth referred to in this paper as slot[1]. In particular, various QoS parameters such as the vector of instantaneous bit rates, delay and/or total quantity of resources allocated impact the values of the *correlated marginal utilities* and the overall expected level of users' satisfaction. This format of the utility functions enables an accurate quantification of the user-perceived QoS. History-dependent utility functions have been originally proposed in [7] for auction-based resource allocation in UMTS networks and subsequently used by other works [8], [14].

In this paper, we propose a 3-tier framework, depicted as Figure2. This framework uses *QoS-aware history-dependent* utility functions so as to quantify the satisfaction of the ad hoc users from the way their services are allocated bandwidth, due to the short time scale operations of the fairness protocol. In particular, we use a classification of user services, based on the QoS parameters that are of importance, in order to define a utility function for each service class. These utility functions are additive, i.e. defined as the sum of marginal utilities attained at the small time scales on which the ad hoc fairness protocols operate. The values of these marginal utilities are

[1]The value of the slot depends on the operation of the underlying routing and ad hoc fairness protocol; a reasonable value for the slot is 1 sec. This value also suffices to capture the impact of QoS variations on user's attained QoS and subsequently the utility attained.

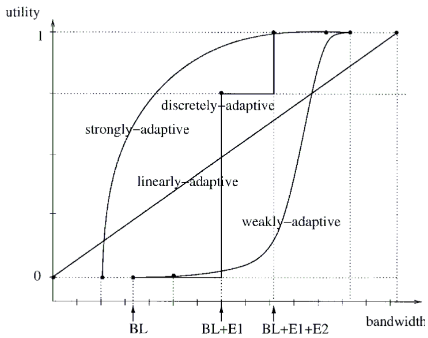

Figure 1: Typical utility functions. Source: [13].

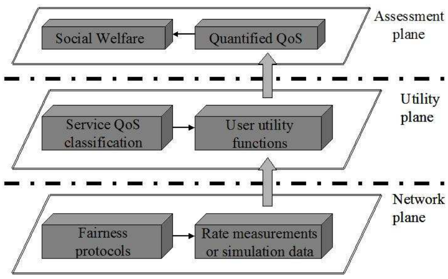

Figure 2: The proposed utility-based framework.

coupled and depending on the service type and the treatment of the user's flow by the ad hoc network vary so as to express the user's satisfaction for the quality of service experienced. Thus, in order to comparatively assess the performance of MANET fairness protocols, it suffices to input the values of the rates of the user flows of the ad hoc network obtained either by real time measurements or simulations (Network plane) to the framework's utility functions (Utility plane). The latter outputs both the per-flow user-perceived QoS and the social welfare (Assessment plane), which are the performance values of the protocols under investigation. Note that social welfare is a widely used performance evaluation metric. It is also indicative of the acceptance of the proposed fairness schemes in practice; schemes that typically produce low values of social welfare are expected to be of limited acceptance by the users.

We claim that our approach is novel and can serve for the ad hoc research community as an economic-aware performance evaluation tool of the various ad hoc fairness protocols. In this paper, we demonstrate this by utilizing our framework in order to perform a comparative assessment of the scheme of [19] with the standard IEEE 802.11.

3 Services and QoS

Prior to proceeding with the definition of the user utility functions, we focus on the various types of user services and their corresponding QoS requirements. There has been already substantial work in the context of UMTS networks by the 3GPP, in identifying the important QoS parameters of services and classifying them thereof. In particular, 3GPP report TS 23.107 [1] defines four QoS classes, namely *conversational*, *streaming*, *interactive* and *background*. Conversational and streaming class both pertain to delay-sensitive services such as voice and real-time audio/video streaming respectively. The prominent QoS factors for both these classes are the *guaranteed bit rate* and the *delay*. Interactive and background class are well-suited to throughput-sensitive delay-tolerant applications, such as Web browsing and email (or downloading) respectively, for which the quantity of accumulated data is of prominent importance. In our work, we use these QoS classes and their respective dominant QoS attributes for the definition of the framework's utility functions. This is performed in the next section of this paper.

4 Utility functions definition

Without loss of generality, we assume that the utility $u_{s,i}$ that user i attains from service s is the sum of the *marginal* utilities attained at every slot t due to the vector of bit rates allocated $< x_i^{(1)}, ..., x_i^{(t)} >$ up to slot t. Thus, $u_{s,i}(x_i^{(1)}, ..., x_i^{(t_{s,i})}) = \sum_{t=1}^{t_{s,i}} v_{s,i}^{(t)}(x_i^{(1)}, ..., x_i^{(t)})$. In this formula, $t_{s,i}$ is the duration of the user's service session and $x_i^{(t)}$ is the bit rate allocated to user i at slot t. Depending on the class of each service, we need to define an appropriate form of $v_{s,i}^{(t)}(x_i^{(1)}, ..., x_i^{(t)})$. For brevity reasons we henceforth denote $v_{s,i}^{(t)}(x_i^{(1)}, ..., x_i^{(t)})$ as $v_{s,i}^{(t)}$.

4.1 Streaming class

The services which comprise the streaming class are delay and rate sensitive, such as real time streaming audio/video. For these services, we assume that there is a minimum bit rate r_0 under which the quality of the service is unacceptable for the user. This assumption has been verified by works on subjective QoS in wireless networks [22], [9], [4].

We denote the corresponding marginal utility from being serviced constantly with a rate r_0 as v_0[2]. Any bit rate less than r_0 results in zero marginal utility for the user. Any additional quantity of bandwidth results in extra value $\Delta V_s \cdot f(x_i^{(t)}, tp_i)$ that depends on both the quantity of bandwidth $x_i^{(t)}$ allocated, as well as whether the user type tp_i is (a) discretely-adaptive, (b) linearly-adaptive, or (c) strongly-adaptive (see Figure1). ΔV_s denotes the extra satisfaction of the user if she were awarded the entire network channel capacity C, while $f(.)$ is an increasing function of bandwidth whose form depends on the user's type and whose range is $[0, 1]$. The marginal utility is also multiplied with the $\alpha_s^{d_i}$ coefficient, where $\alpha_s \in (0, 1)$ and d_i is the distance between the current and the previous slot during which a rate at least equal to r_0 was allocated to user i. Hence, the marginal utility is reduced if the user is not served satisfactorily for several slots, due to the incurred

[2]For both r_0 and v_0 we omit the service subscript s for clarity reasons.

service interrupts (i.e. application content "freezes") and the corresponding high values of delay for delivering the service content. Therefore:

$$v_{s,i}^{(t)} = \begin{cases} [v_0(s,i,t) + \Delta V_s \cdot f(x_i^{(t)}, tp_i)] \cdot \alpha_s^{d_i} & \text{, if } x_i^{(t)} \geq r_0 \\ 0 & \text{, if } x_i^{(t)} < r_0 \end{cases}$$

Note also that $v_0(s,i,t)$ fluctuates over time rather than being constant. This way, the marginal utility has a "memory" of the quality degradation experienced in the past and fluctuates accordingly. We define:

$$v_0(s,i,t) = \begin{cases} v_0 & \text{, if } t = 0 \\ \frac{1}{\sqrt{d_i}} \cdot v_0 & \text{, if } d_i > 1 \\ \max\{v_0, v_0(s,i,t-1) + \beta \cdot v_0\} & \text{, if } d_i = 0 \end{cases}$$

where $\beta \in (0,1)$. In order to complete the definition, we also need to define $f(x_i^{(t)}, tp_i)$. For this definition, we use some standard functions that other researchers have used in their works [15], [13]:

$$f(x_i^{(t)}, tp_i) = \begin{cases} \frac{x_i^{(t)} - r_0}{C - r_0} & \text{, if } tp_i = \text{linearly-adaptive} \\ \frac{log(x_i^{(t)} - r_0)}{log(C - r_0)} & \text{, if } tp_i = \text{strongly-adaptive} \end{cases}$$

Finally, for discretely-adaptive users, we define $f(x_i^{(t)}, tp_i)$ to be a step function whose steps are the points of the linearly-adaptive utility function, taken from $x_0 = r_0$ and for every step kb/s. Thus, the step utility function of this type of users is a discretization of the utility function used for linearly-adaptive users.

Concluding, the utility definition for streaming class services captures the effect of dissatisfaction stemming from both a) low bit transfer rates, since this results in both zero marginal utility and a reduction of the value of $v_0(s,i,t)$, and b) the duration of these service interrupts, which affect the values of the delay of the content delivery of the service, by multiplying the value of the marginal utility with the $\alpha_s^{d_i}$ coefficient whenever satisfactory service is resumed. It is also worth noting that the extra units of bandwidth allocated on top of r_0 result in different marginal returns of ΔV_s, depending on user's type, so as to cover all possible types of users.

4.2 Conversational class

As explained in Section 4, the services of the conversational class are affected by the same QoS parameters with the streaming class services. The difference is that the impact of delay results in faster and higher degradation of the user-perceived QoS. Therefore, it suffices to use the utility function definition of the streaming class modified only so that a steeper reduction of the marginal utility $v_0(s,i,t)$ occurs in cases of service interrupts. Therefore, $v_0(s,i,t)$ for the conversational class is defined as follows:

$$v_0(s,i,t) = \begin{cases} v_0 & \text{, if } t = 0 \\ \frac{1}{d_i} \cdot v_0 & \text{, if } d_i > 1 \\ \max\{v_0, v_0(s,i,t-1) + \beta \cdot v_0\} & \text{, if } d_i = 0 \end{cases}$$

4.3 Background and interactive class

Background and interactive class pertain to delay-tolerant throughput-sensitive services, such as data downloading. Though these services are not QoS-sensitive, for completeness reasons we also define the marginal utility for these services as well. In particular, it suffices to define it as the product of the rate allocated at each slot times a constant utility coefficient v_0. Thus, $v_0(s,i,t) = v_0 \cdot x_i^{(t)}$.

4.4 Discussion

The utility functions definitions of this section are essentially not unique. This is is not important per se for the assessment our framework performs, as long as a) these definitions are rational, i.e. reflect the impact of the QoS parameters of importance on user utility and b) the *same utility definitions* are used for the comparative assessment of the protocols. Thus, the absolute values of the user-perceived QoS obtained by inputting the allocated rates under these protocols to the respective utility functions are not important, but their ordering is. This ranking is insensitive to the actual utility functions definitions and depicts which schemes perform better and for what kind of services, thus providing insight to the inherent properties and performance of the various ad hoc fairness schemes.

5 Usefulness of framework: Assessing fairness in ad hoc networks

We demonstrate the usefulness of our framework by using it to comparatively assess the performance of the scheme of [19] and standard IEEE 802.11; note however that it can be used for any fairness scheme. An extensive comparative assessment was conducted. However, due to space limitations, a subset of the results attained for traffic comprising only of streaming flows are presented in this section; more results can be provided in the full version of this paper.

The scheme of [19] was designed to solve some of the fairness issues we observe with the IEEE 802.11 standard. By exchanging rate information at the routing layer, this scheme computes the rates achievable by the MAC layer so that all flows are granted a part of the capacity according to a proportional fairness rationale. The ns2 simulator version 2.33, the protocol implementation code of [19] and a set of Perl scripts implementing the Utility and Assessment plane of the framework (see Figure2) comprise the software used for this assessment.

Each experiment is conducted for T slots (seconds) over a square $S \times S$ terrain. Each slot is in fact a separate simulation of $100s$ for which we compute the bandwidth in the last 20 seconds. By doing so, we perform a long-term fairness evaluation of the scheme of [19] without the latter's performance being affected by the protocol convergence and routing issues. The mobility model adopted prescribes that each node decides at every slot whether to move for δ meters with a probability p_{move}; the angle of the node's movement from its current position is drawn from a uniform distribution having support in $[0, 360)$. For both schemes assessed, each set of experiments regards the same number of streaming video flows F crossing the network, whose start slot of transmission, origin and destination are randomly selected. These flows are simulated as aggressive UDP/CBR flows. The parameters for ns2 are depicted as Table 1, while the utility functions parameters are $u_0 = 10$, $\alpha_s = 0.97$, $\beta = 0.1$, $\Delta V_s = 5 \cdot u_0$.

Physical rate	11 Mbps
Real throughput	5 Mbps
Routing protocol	AODV
Transmission range	200 m
Carrier sensing range	397 m
Capture threshold	10 dB
Radio propagation model	TwoRayGround
Packet size	1000 Bytes
RTS/CTS	disabled

Table 1: Summary of the ns2 simulation parameters.

The first set of experiments depicts the typical performance of the two schemes which are evaluated. It regards the transmission of 5 video flows over a MANET of 20 nodes deployed on a $500m \times 500m$ terrain. Since the total channel utilization can be slightly higher without rate control, one could suppose that this scheme performs better also in terms of user utilities and social welfare. However, this is not the case due to the higher variance of the rates of each flow. Figure3 and Figure4 depict the typical rates attained in our experiments. The framework's utility functions capture this effect, as depicted in Figure5, where the average social welfare over all simulations is displayed: in terms of social welfare, a protocol that allocates bandwidth regularly such as [19] performs much better.

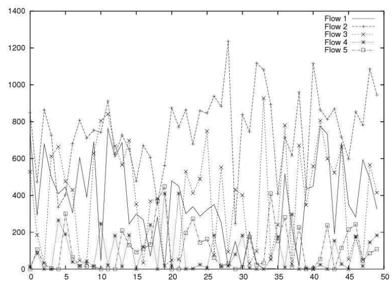

Figure 3: Rates attained under IEEE 802.11.

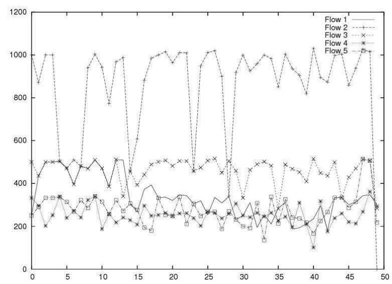

Figure 4: Rates attained under the scheme of [19].

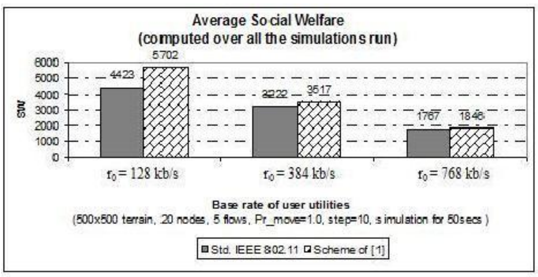

Figure 5: Social welfare for a 500x500 terrain.

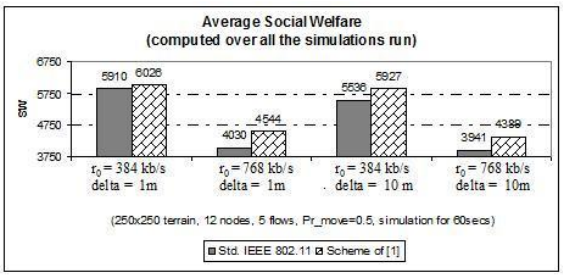

Figure 6: Social welfare for a 250x250 terrain.

The second group of experiments regards the transmission of 5 video flows over a MANET of 12 nodes, which are randomly deployed on a terrain size of $250m \times 250m$. Since all communicating nodes are expected to be in carrier sensing range, this is the most favorable case for the performance of the standard IEEE 802.11 protocol. In order to assess the impact of mobility, we comparatively assess the performance of the protocols for $p_{\text{move}} = 0.5$ with δ being set to 1 and 10 respectively for two subsets of 15 experiments. The channel utilization is similar for both schemes. In particular, for the first subset of experiments ($\delta = 1m$) the standard IEEE 802.11 results in 1.47% higher utilization, while under higher mobility ($\delta = 10m$) the scheme of [19] is 1.05% better. However, the scheme of [19] is *always strictly better* in terms of social welfare for all the experiments conducted and for all the flows and types of users (i.e. linearly-adaptive, strongly-adaptive and discretely-adaptive). In fact, the higher the base rate r_0 of the flows, the higher the difference in performance becomes. The average social welfare attained over each set of 15 experiments is depicted as Figure6. Finally, the performance of both schemes is close to 0 for high values of r_0 if the medium is saturated; this is to be expected since under congestion it is always impossible for the flows to attain a high bit rate throughout the service time.

Overall, the utility-based framework captures the inherent properties of the schemes under investigation. Fairness schemes, as [19], allocate smoother rates over time; this is very desirable for multi-hop QoS-sensitive flows, thus resulting in higher values of the social welfare attained for a relatively small expense of channel utilization.

6 Conclusions

In this paper, we have presented a utility-based framework, based on *QoS-aware history-dependent* utility functions. These functions quantify the satisfaction that the users of the MANETs obtain from the way their long-lived service sessions are allocated bandwidth, due to mobility and the behavior of the fairness protocols proposed for ad hoc networks. We have argued that our approach is novel and can serve as an economic-aware performance evaluation tool of the various ad hoc fairness protocols. Finally, we have demonstrated the framework's usefulness, by performing a comparative assessment of the fairness scheme of [19] with the standard IEEE 802.11. Using our framework so as to perform an in-depth study of the relationship of fairness and QoS in ad hoc networks, as well as a detailed evaluation of more fairness schemes, comprise interesting topics of future research.

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