Incentive Compatible MAC-Layer QoS Design

Jennifer Price
Department of Electrical and Computer Engineering
University of California, San Diego
La Jolla, CA 92093
jenn-price@ucsd.edu

Pavan Nuggehalli
Calit2
University of California, San Diego
La Jolla, CA 92093
pnuggehalli@soe.ucsd.edu

Tara Javidi
Department of Electrical and Computer Engineering
University of California, San Diego
La Jolla, CA 92093
tara@ece.ucsd.edu

***Abstract*— The implementation of QoS provisioning at the MAC layer requires users to classify their traffic into QoS categories. In realistic scenarios where users are selfish and interested in maximizing their own utility, users may have an interest in misrepresenting the QoS category of their traffic. We examine a simplified model for IEEE 802.11e networks in which channel access can be obtained via random access or polling. Using concepts from game theory, we show that a polling based incentive mechanism can stimulate users to truthfully report the QoS category of their traffic. Furthermore, we show that our incentive mechanism improves the system capacity, in terms of the number of QoS constrained users that can be admitted, when users are strategic.**

I. Introduction

Quality of Service (QoS) provisioning has become an important aspect of MAC layer design in networks where elastic traffic (e.g. data) and real-time traffic (e.g. voice and video) coexist. In such networks, it is important to provide good delay performance to real-time traffic, while still maintaining acceptable throughput levels for elastic traffic. In 802.11e networks, QoS differentiation is accomplished by classifying traffic into priority classes. Users maintain separate queues for each priority class, and packets in each queue contend for the channel with a probability that is dependent on the priority class. In other words, high priority traffic contends for the channel more aggressively than low priority traffic.

The random-access nature of uplink in the 802.11 protocol is inherently distributed; that is, users self-classify the priority of their own traffic. In a scenario where users are well-behaved, then the network can trust users to correctly classify their traffic. But in realistic scenarios where users are strategic, they may have an interest in misrepresenting the priority of their traffic - even at the expense of overall network performance. For example, a user can improve the throughput of its low-priority traffic by classifying it as high-priority - an action that adversely impacts the performance of other users. If all users act similarly (as rational users can be expected to do), then the system no longer supports any QoS differentiation - a phenomenon known as the *tragedy of commons* [1].

In order to gain insight about how to design incentive-compatible schemes for MAC-layer QoS, we work with a slotted aloha-type model that retains many of the salient features of 802.11e, but with the benefit of admitting tractable analysis. With this model, each user has two types of traffic: high priority (delay sensitive) traffic, and low priority (delay tolerant) traffic. The network can operate in one of two phases: contention, or contention-free. During the contention phase, users contend for the channel with a given probability, similar to the enhanced distributed coordination function (EDCF) in 802.11e. During the contention-free phase, the AP polls a single user who is then given dedicated access to the channel, similar to the HCF controlled channel access (HCCA) in 802.11e [2]. Note that since users are QoS constrained, the system can only admit a finite number of users. We defined system capacity as the maximum number of users that can be admitted under the constraint that their QoS requirements are met.

The main contributions of this paper are two-fold. First, we show that the appropriate design of a polling scheme can be used to incentivize users to correctly classify their traffic, thus enabling QoS differentiation. Second, our scheme strictly improves system capacity compared to the scenario when users are strategic and no incentive mechanisms is in place. Observe that our incentive scheme can be extended in a straight-forward fashion to the IEEE 802.11e standard and, in fact, can be implemented without any modification to the current standard.

The impact of selfish behavior on resource allocation in communication networks has been well studied [3]-[5]. A common way to combat this selfish behavior is the use of dollar-valued pricing schemes, in which users pay for the service they receive [6]-[8]. Such schemes may, however, require the implementation of complex pricing schemes where prices are updated, for example, at the rate of channel variations or changes in network topology. Since access to wireless networks is typically free or available at a flat rate, this is a less-than-desirable solution.

Recently, researchers have begun to consider alternatives to dollar-valued pricing schemes. In wireless networks, one technique is to model energy as an explicit cost to users [9], [10]. The authors in [11] use a centralized downlink scheduler to ensure socially optimal uplink allocations in cellular networks. The authors in [12] consider a scenario similar to the one presented here. However, the system model is different and requires users to be either high-priority or low-priority. Moreover [12] does not consider admission control. The analysis and results in this paper are completely novel.

The rest of this paper is organized as follows. Section II presents the system model, while Section III formulates the optimal resource allocation problem in terms of admission control. Section IV formulates the traffic classification problem as a non-cooperative game, and shows that it is possible to design a polling rule such that correctly classifying traffic is a dominant strategy for all users. Section V gives numerical results regarding the impact of selfish users on the admission control criteria, throughput and delay performance. Finally, Section VI provides our conclusions and areas of future work.

II. System Model

Throughout this paper, we use the following model. There are N users, each with high-priority (HP) and low-priority (LP) traffic. To simplify our analysis, we assume that both sets of queues are saturated (i.e. full-buffer assumption). Furthermore, the system guarantees a minimum QoS to users in the form of minimum throughput guarantees: T^H for HP traffic and T^L for LP traffic.

Time is divided into slots. Each slot operates in either the contention phase (CP) or the contention-free phase (CFP). We denote by α the probability that a slot operates in CFP, where α is a fixed-value chosen by the AP. In each slot of the contention-free phase, the AP polls a single node, where v_i is the probability that node i is polled. The polled node may choose to send either HP or LP traffic.

During the contention phase, HP queues attempt to transmit with probability p, while LP queues attempt to transmit with probability $q < p$. We assume that users exercise internal collision resolution; that is, if a user attempts to transmit from both its HP and LP queues in the same slot, only the HP queue will actually contend for the channel. A transmission attempt is successful if and only if there is a single transmission attempt - there is no capture or carrier sensing, and we do not model an explicit backoff mechanism.

With this in mind, we can write the throughput of users as follows:

$$\tau_i^H = (1-\alpha)p\left[1-(p+q(1-p))\right]^{N-1}$$

$$\tau_i^L = (1-\alpha)q(1-p)\left[1-(p+q(1-p))\right]^{N-1}$$

$$\tau_i^{poll} = \alpha v_i$$

where τ_i^H is the HP throughput, τ_i^L is the LP throughput, and τ_i^{poll} is the contention-free phase throughput for user i.

III. Optimal System Performance

For most current applications, the *traditional* mode of operation for 802.11e networks is to operate solely in the contention phase and without any admission control. There are two drawbacks to this design. The first is that in contention-based systems, increasing the number of users increases contention. As a result, the AP cannot provide minimum throughput guarantees for an arbitrary number of users. The second drawback is that the choice of transmission probabilities $q < p$, although motivated by the delay sensitivity of high priority traffic, is unfair to LP traffic. A user can improve the throughput of its low-priority traffic by classifying it as high-priority - an action that adversely impacts the performance of other users. Since throughput depends on the number of users in the system, the AP can provide minimum throughput guarantees by simply limiting the number of users in the system. In order to address the second issue, we use the contention free phase. The idea is to assign the probability that a given node is polled based on its behavior during the contention phase. If a user is "truthful" in classifying its LP traffic, it is rewarded with a higher value of v_i. If a user is "strategic" in classifying its LP traffic, it is punished by receiving a lower (possibly '0') value of v_i. Of course, this type of scheme requires that the AP be able to determine whether a node is transmitting its LP traffic with probability p or q. While the transmit probability is not directly observable, the broadcast nature of transmissions in 802.11e means that the AP can easily infer these probabilities by keeping a filtered version of transmission attempts, along the lines of the approach taken by the authors in [4].

Note that because HP and LP throughput are dependent on the proportion of time spent in CFP, the admission control criteria becomes a function of α. Furthermore, since we are using polling probabilities as a reward or punishment for users' behavior, and since users can choose to transmit either HP or LP traffic when polled, the minimum throughput requirements should be met regardless of how much polling time a user receives. In other words, the admission control criteria is dependent on the value of α, but it does not depend on the values of $\underline{v}$.

A. Truthful Users

From the perspective of the AP, the utility of the system is the number of admissible users. If users are assumed to be truthful in classifying their traffic, the AP will choose α and N to solve the following problem.

<u>Problem P1</u>

$$\max_{\alpha,N} \; N$$

subject to

$$(1-\alpha)p\left[1-(p+q(1-p))\right]^{N-1} \geq T^H \quad (1)$$

$$(1-\alpha)q(1-p)\left[1-(p+q(1-p))\right]^{N-1} \geq T^L \quad (2)$$

Here, we present a technical assumption regarding the relationship between T^H, T^L, p, and q.

Technical Assumption 1: The values of T^H, T^L, p, and q are such that $\frac{T^H}{T^L} \geq \frac{p}{q(1-p)}$.

Now, consider the constraints from Problem P1. By rearranging, we get

$$\alpha \leq 1 - \frac{T^H}{p\left(1-(p+q(1-p))\right)^{N-1}}$$

$$\alpha \leq 1 - \frac{T^L}{q(1-p)\left(1-(p+q(1-p))\right)^{N-1}}$$

But from Technical Assumption 1, we have $\frac{T^H}{p} \geq \frac{T^L}{q(1-p)}$, making the first condition sufficient to guarantee the second.

Since the upper bound on α given by (1) is a strictly decreasing function of N, the solution to Problem P1 is to choose $\alpha = 0$. This is not surprising. If users can be trusted to be truthful and transmit their LP traffic with probability q, there is no need to invoke the contention-free phase as a reward or punishment. From the perspective of the AP (which is trying to maximize the number of users allowed into the system), the best course of action is to always operate in contention phase.

B. Strategic Users

Problem P1 formulates the admission control criteria based on the assumption that users are truthful. If users are strategic, however, the AP cannot support minimum throughput guarantees or desirable delay performance by using the admission control criteria from (1). One way to mitigate this problem is to simply construct the admission control criteria under the assumption that all users are strategic. In this case, the AP will choose α and N to solve the following problem.

Problem P2

$$\max_{\alpha,N} \; N$$

subject to

$$(1-\alpha)p\left[1-(p+p(1-p))\right]^{N-1} \geq T^H \quad (3)$$

$$(1-\alpha)p(1-p)\left[1-(p+p(1-p))\right]^{N-1} \geq T^L \quad (4)$$

From Technical Assumption 1, we have $\frac{T^H}{p} \geq \frac{T^L}{q(1-p)} \geq \frac{T^L}{p(1-p)}$, making (3) sufficient to guarantee (4).

Although solving Problem P2 allows the AP to satisfy minimum throughput guarantees if users are strategic, it does nothing to ensure the appropriate QoS differentiation (i.e. the delay performance of HP traffic). In the next section, we use tools from game-theory to show how the contention-free phase can be used to incentivize users to be truthful.

IV. Non-Cooperative Game

We formulate a Stackelberg multi-stage game with two types of players: the AP and the users. The AP is a benevolent player whose only goal is ensure that users transmit LP traffic with probability q. The users are selfish players interested in maximizing their own utility. The game is structured such that the values of α and N are fixed and known, and users know apriori that their polling probabilities will be assigned according to some rule based on the actions of the players. In this case, v_i is chosen as $\frac{1}{\text{number of truthful players}}$ if player i is truthful, and $'0'$ otherwise. Since this is formulated as a one-shot game, users are modeled as announcing their choice of transmit probability to the AP. In reality, the AP would observe the frequency of transmission attempts over some period of time and assign polling probabilities based on its observations.

A. Game Formulation

Formally, we denote by $F = [\mathcal{N}, \{\Sigma_i\}, \{U_i(\cdot)\}]$ the non-cooperative game. Let $\mathcal{N} = \{0, 1, \ldots, N\}$ denote the set of players, where player $i = 0$ is the AP and players $i = 1, \ldots, N$ are the users. The strategy space for the AP is $\Sigma_0 = \{\underline{v} : 0 \leq v_i \leq 1, \sum_{i=1}^{N} v_i \leq 1\}$, and for the users is $\Sigma_i = \{p, q\}$. Notice that the strategy space for users is purposely restrictive; that is, the misbehavior of users is restricted to transmitting LP traffic with probability p. Users are not allowed to modify protocol parameters by using arbitrary transmission probabilities[1], nor are users strategic with respect to their HP traffic. We denote by $\sigma_i \in \Sigma_i$ the action of user i, and by $\sigma_{-i} = (\sigma_1, \ldots, \sigma_i - 1, \sigma_{i+1}, \sigma_N)$ the actions of the other users.

[1]This reflects realistic situations in which users have the ability to declare the priority of their traffic, but do not have access to MAC-layer parameters.

Since users are not strategic with respect to their HP traffic, we need only model the utility of LP traffic. Since LP traffic is delay tolerant, it is reasonable to model LP utility as a function of throughput. We have

$$\begin{aligned} U_i(\sigma_i, \sigma_{-i}, v_i) &= \tau_i^L + \tau_i^{poll} \\ &= (1-\alpha)\sigma_i(1-p)\prod_{j\neq i}\left[1-(p+\sigma_j(1-p))\right] \\ &+ \alpha v_i \end{aligned}$$

Since the AP is a benevolent player whose only goal is to ensure QoS differentiation, the utility of the AP is defined as $U_0(\underline{\sigma}, \underline{v}) = 0$.

B. Dominant Strategies Equilibrium

Having constructed our game, we want to see whether an appropriate choice of $\underline{v}$ incentivizes users to transmit their LP traffic with the correct probability. Let $I(\sigma_i) = \begin{cases} 1 & \text{if } \sigma_i = q \\ 0 & \text{else} \end{cases}$ be an indicator function for whether user i transmits LP traffic with the correct probability. The polling probabilities assigned by the AP can be written as

$$v_i = \frac{I(\sigma_i)}{\sum_{j=1}^{N} I(\sigma_j)} \quad (5)$$

Recall the definition of dominant strategies equilibrium [1]:

Definition 1: A strategy profile σ is a dominant strategies equilibrium if and only if

$$u_i(\sigma_i, \sigma_{-i}) \geq u_i(\sigma_i', \sigma_{-i}) \; \forall \sigma_i' \in \Sigma_i \; \forall \sigma_{-i} \in \Sigma_{-i}$$

for every player i.

It is our goal to show that if the AP assigns polling probabilities according to (5), transmitting LP traffic with probability q is a dominant strategy equilibrium of Game F *for certain values of* α *and* N. We now introduce the following theorem.

Theorem 1: Let α and N be such that

$$\alpha \geq \frac{N(1-p)(p-q)(1-p-q(1-p))^{N-1}}{1+N(1-p)(p-q)(1-p-q(1-p))^{N-1}} \quad (6)$$

and let $\sigma = \left\{\left(\frac{I(\sigma_1)}{\sum_{j=1}^{N} I(\sigma_j)}, \ldots, \frac{I(\sigma_N)}{\sum_{j=1}^{N} I(\sigma_j)}\right), q, \ldots, q\right\}$. Then the strategy profile σ is a dominant strategies equilibrium for game F.

Proof: Since the AP is a benevolent user without any inherent utility, we only need to show that

$$\tau_i^L(q, \sigma_{-i}) + \tau_i^{poll}(q, \sigma_{-i}) - \tau_i^L(p, \sigma_{-i}) + \tau_i^{poll}(p, \sigma_{-i}) \geq 0$$

for every user $i = 1, \ldots, N$ and for every $\sigma_{-i} \in \bigotimes_{j\neq i} \Sigma_j$.

We have:

$$\begin{aligned} \tau_i^L &\quad (q, \sigma_{-i}) + \tau_i^{poll}(q, \sigma_{-i}) - \tau_i^L(p, \sigma_{-i}) - \tau_i^{poll}(p, \sigma_{-i}) \\ = &\quad (1-\alpha)q(1-p)\prod_{j\neq i}\left[1-(p+\sigma_j(1-p))\right] \\ + &\quad \frac{\alpha}{\sum_{j\neq i} I(\sigma_j)} \\ - &\quad (1-\alpha)p(1-p)\prod_{j\neq i}\left[1-(p+\sigma_j(1-p))\right] + 0 \\ \geq &\quad (1-\alpha)(q-p)(1-p)\prod_{j\neq i}\left[1-(p+\sigma_j(1-p))\right] + \frac{\alpha}{N} \\ \geq &\quad 0 \end{aligned}$$

where the first inequality comes from $\sum_{j=1}^{N} I(\sigma_j) \leq N$, and the last inequality comes from (6) and from $[1-(p+\sigma_j(1-p))] \leq 1-p-q(1-p)$. ∎

C. System Performance Revisited

We are interested in maximizing the number of users that can be admitted subject to both QoS and incentive compatibility constraints. We have

Problem P3

$$\max_{\alpha,N} \; N$$

subject to

$$\alpha \;\leq\; 1-\frac{T^H}{p\left(1-(p+q(1-p))\right)^{N-1}} \quad (7)$$

$$\alpha \;\geq\; \frac{N(1-p)(p-q)(1-p-q(1-p))^{N-1}}{1+N(1-p)(p-q)(1-p-q(1-p))^{N-1}} \quad (8)$$

The first constraint is the same as in Problem P1 - it ensures the number of users is such that each user receives $\tau_i^H \geq T^H$ and $\tau_i^L \geq T^L$. In addition to this bound, there is a lower bound on α that must be satisfied in order to incentivize users. Again, this solution is not surprising. In order to incentivize users, the AP must invoke the contention free phase.

Let N_1^* be the solution to Problem P1, N_2^* be the solution to Problem P2, and N_3^* be the solution to Problem P3. In order to examine the impact of strategic users, we draw on terminology from economics. Often, the equilibrium points that arise from a non-cooperative game are sub-optimal with respect to system performance. One way to quantify this sub-optimality is the *price of anarchy* [5], defined as:

$$\rho_A = \frac{\text{system utility of worst equilibrium}}{\text{optimal system utility}} = \frac{N_2^*}{N_1^*}$$

In other words, the price of anarchy characterizes the loss in overall system utility that is caused by the non-cooperative behavior of users.

The incentive-compatible scheme introduced in this paper also results in a loss in system utility, since invoking the contention-free phase decreases the number of users admissible to the system. Following the definition introduced in [11], we can quantify this loss using the *cost of incentive compatibility*, defined as:

$$\rho_{IC} = \frac{\text{system utility of incentive-compatible scheme}}{\text{optimal system utility}} = \frac{N_3^*}{N_1^*}$$

The distinction between these two measures is that the price of anarchy measures the loss in system utility that occurs when users are strategic, while the cost of incentive compatibility measures the loss in system utility that is caused by incentivizing users to be truthful.

V. Numerical Results

In this section, we examine the behavior of our proposed scheme through numerical examples.

Figure 1 shows the upper and lower bounds on α as a function of N when $p = .05$. $q = .01$, $T^H = .01$ and $T^L = T^H \frac{q(1-p)}{p}$. The dotted line shows the upper bound

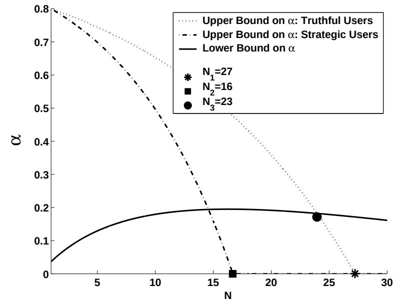

Fig. 1. Upper and Lower Bounds on α as a Function of N

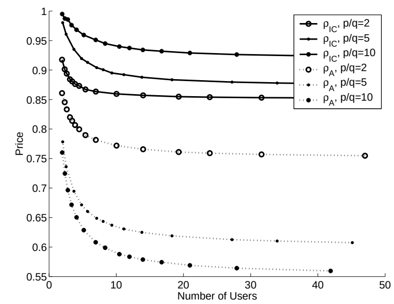

Fig. 2. Comparison of Price of Anarchy and Cost of Incentive Compatibility

on α for which the minimum throughput guarantees can be met if all users are truthful. Since we must have $\alpha \geq 0$, the maximum number of users admissible to the system is 27, and occurs when $\alpha = 0$. The dashed line shows the upper bound on α for which the minimum throughput guarantees can be met if users are strategic. Again the maximum number of users admissible to the system occurs when $\alpha = 0$. When users are strategic, however, this value is only 16. The solid line shows the lower bound on α for which transmitting LP traffic with probability q is a dominant strategy. In order to incentivize users while still maintaining minimum throughput guarantees, we must choose an α that satisfies both the upper bound (given by the dotted line) and the lower bound (given by the solid line) from Problem P3. The largest value of N for which this is possible is 23, and occurs at the point where the upper and lower bounds cross.

In this example, the price of anarchy is $\rho_A = \frac{16}{27} = .59$ and the cost of incentive compatibility is $\rho_{IC} = \frac{23}{27} = .85$. Using the contention-free phase of 802.11e to incentivize users not only maintains the desired QoS differentiation, but it actually performs better in terms of admission control than simply allowing for the fact that users are strategic. A natural question is whether this is true in general. Figure 2 compares the price of anarchy and the cost of incentive compatibility as a function of N_1^* (the number of users admissible to the system when users are truthful). This comparison is done for three different of QoS differentiation: $\frac{p}{q} = 2$, $\frac{p}{q} = 5$, and $\frac{p}{q} = 10$.

These results indicate that our proposed scheme does perform better in terms of admission control than simply allowing for the fact that users are strategic. Perhaps the most interesting observation, however, is that the cost of incentive compatibility for our scheme actually improves as the QoS differentiation increases! This is in stark contrast with the policy of simply

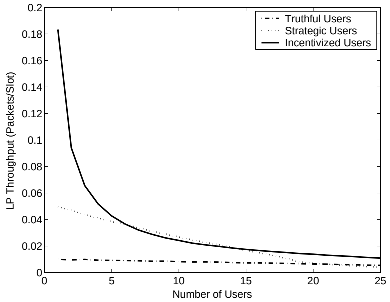

Fig. 3. Average Throughput of LP Traffic

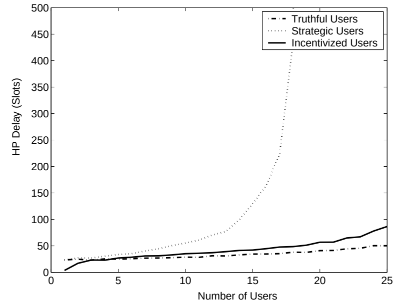

Fig. 4. Average Delay of HP Traffic

allowing for the fact that users may cheat, for which the price of anarchy worsens as the QoS differentiation increases.

We used simulation to study the delay performance of our scheme. Each user's high priority queue sees a poisson arrival process, with arrival rates homogenous across users. Low-priority queues are saturated. Users attempt to transmit high-priority traffic (when it is available) according to a bernoulli random variable with parameter p, and low-priority traffic according to a bernoulli random variable with parameter q. Internal collision resolution is modeled in favor of high-priority traffic. The probability of operating in the contention-free phase in any given slot is modeled as a bernoulli random variable with parameter α. Once in contention-free phase, the AP polls a single user. Users are equally likely to be polled. If the polled users' high-priority queue is non-empty, it sends a high-priority packet. Otherwise, it sends a low-priority packet. We use values $p = .05$, $q = .01$, $T^H = .01$, and $T^L = T^H \frac{q(1-p)}{p}$. When implementing the contention-free phase we use $\alpha = .0821$, which corresponds to the value $N_3^* = 23$ from Figure 1.

Figures 3 and 4 show the throughput performance of low-priority traffic and the delay performance of high-priority traffic for three different scenarios: the case when users are truthful and contention-free phase is not used, the case when users are strategic and contention-free phase is not used, and the case when the contention-free phase is used to incentivize users to be truthful. We see from Figure 3 that users receive higher throughput for LP traffic when they are strategic as compared to when they behave. This is precisely the reason we need to incentivize users. Our proposed scheme gives LP throughput comparable to what users receive when they are strategic, and for large numbers of users our scheme actually gives higher LP throughput.

Figure 4 shows one of the most important features of our proposed scheme - namely, desirable delay performance for HP traffic. We see that the delay performance of our proposed scheme is strictly better than the delay performance achieved when users are strategic. In fact, as the number of users grows, the system can no longer support minimum throughput guarantees for HP traffic when users are strategic. This is what causes the delay to grow exponentially in the case when users are strategic. We see that by incentivizing users, the delays remain stable for a larger number of users (this is exactly the phenomenon described above using price of anarchy and price of incentive compatibility). Furthermore, we see that our scheme actually gives HP delay performance comparable to that of the "optimal" system, in which users are truthful and 802.11e operates only in contention-phase.

VI. Conclusion

In this paper, we have presented a scheme that incentivizes users to correctly classify the priority of their traffic in 802.11e systems. By using contention-free operation and designing appropriate rules for polling probabilities, we have shown it is possible to construct a scheme in which it is a dominant strategy for users to transmit their low-priority traffic with the correct probability. Furthermore, we have shown that this scheme improves the throughput performance of LP users as compared to the traditional operation of 802.11e, while maintaining desirable delay performance for high priority users.

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