A Cross-Layer Framework of QoS Routing and Distributed Scheduling for Mesh Networks

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***Abstract*—Cross-layer routing and scheduling algorithms design for wireless backhaul mesh network has attracted much research interest recently. The network is expected to support various types of applications with different quality of service (QoS) requirements from both routing and scheduling perspectives. Existing works do not efficiently integrate these QoS constraints in route discovery and maintenance phases and overlook the interaction between medium access control (MAC) and routing algorithms. In this work, we propose a novel cross-layer framework of QoS routing and distributed opportunistic scheduling for wireless mesh network, which provides resource reservation for QoS flows. Studies with different scheduling algorithms and routing protocols have shown that our algorithm successfully guarantees various QoS requirements and achieves higher network throughput when compared with other standard techniques.**

I. INTRODUCTION

Wireless mesh networks (WMNs) is a relatively new and promising key technology for next generation wireless networking that have recently attracted both the academic and industrial interest. Mesh networks are expected gradually to partially substitute the wired network infrastructure functionality by being able to provide a cheap, quick and efficient solution for wireless data networking in urban, suburban and even rural environments. Their popularity comes from the fact that they are self-organized, self-configurable and easily adaptable to different traffic requirements and network changes. Mesh networks are composed of static wireless nodes/mesh routers (WMR) that have ample energy supply. Each node operates not only as an conventional access point (AP)/Internet gateway (IGW) to the internet but also as a wireless router (Fig. 1) able to relay packets from other nodes without direct access to their destinations [1]. The destination can be an internet gateway or a mobile user served by another AP in the same mesh network. WMNs must meet a number of technical requirements, such as providing high capacity wireless links and large enough communication range to ensure network connectivity to IGWs, while at the same time must guarantee that the multiple and strict quality-of-service (QoS) applications' constraints are satisfied.

Unfortunately, most of the current work on wireless ad hoc network protocol analysis and design is mainly based on a layered approach. This layered architecture by providing modularity and transparency between the layers, led to the robust scalable protocols in the Internet and it has become the de facto architecture for wireless systems. However, in wireless mesh networks the spatial reuse of the spectral frequency and the broadcast, unstable and error prone nature of the channel, make the layered approach suboptimum for the overall system performance. For instance, a bad resource scheduling in MAC layer can lead to interference that affects the performance of the PHY layer due to reduced Signal-to-Interference-plus-Noise-Ratio (SINR). Local capacity optimization with opportunistic scheduling techniques that exploit the multi-user diversity may increase the overall outgoing throughput of the transceivers but they can also generate new bottlenecks in several routes in the network.

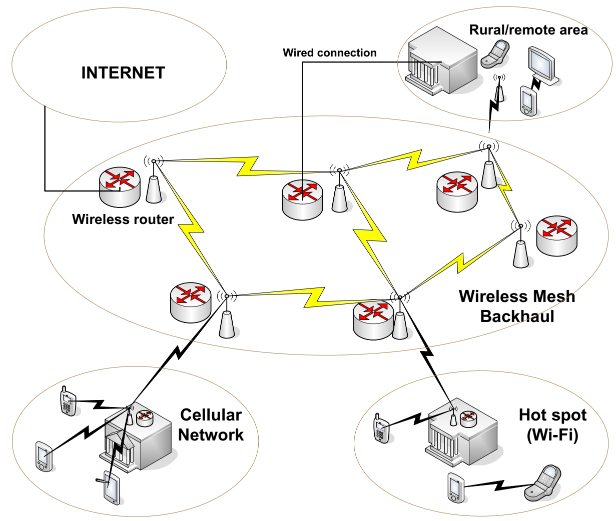

Fig. 1. Typical wireless mesh network scenario.

This is why cross-layer design for improving the network performance has been a focus of much recent work. In a cross-layer paradigm, the joint optimization of control over two or more layers can yield significantly improved performance. Caution needs to be exercised, though, since cross-layer design has the potential to destroy the modularity and make the overall system fragile. Other importance challenges that have to be taken into account during the design of cross-layered solution for WMNs is the different operation time-scales between coding, scheduling and routing algorithms; especially in the case that system performance predictions in different layers have to be performed. Moreover, since WMNs have to support a wide variety of applications and services, there are multi-constrained QoS requirements that have to be jointly satisfied by the cross-layer approach. For instance, additive (i.e., cost, delay, jitter), multiplicative (i.e., packet-error-rate and path break probability) and concave (i.e., throughput) metrics have to be jointly taken into account which has been proven to be NP-complete [13]. In this work we present a heuristic low-complexity cross-layer framework that attempts to tackle the aforementioned challenges and provide multi-constrained QoS support to any WMNs.

Related Work: The well-known Ad hoc on-demand distance vector (AODV) [11] protocol, a reactive approach for route discovery and maintenance that finds the routes with minimum number of hops from source to destination in ad-hoc networks, is not suitable for high throughput and delay-sensitive applications. An extension of AODV, QoS-AODV [15], provides QoS provisioning in terms of both bandwidth and delay. However, it overlooks the packet queuing delay but only the packet processing time was considered in Node Traversal Time. This inaccurate estimation may result in much higher end-to-end (ETE) packet delay than expected when high traffic load is considered. Another bandwidth routing (BR) protocol [8], and a similar on-demand QoS routing (OQR) protocol [7] were proposed to calculate the available bandwidth in terms of slot for QoS flows. However, packet delay is clearly not considered. Furthermore, because slots are pre-determined before traffic flows are scheduled, it fails to exploit the scheduling opportunistic gain in fast-fading channels. In other words, the reserved time slots may deteriorate packet transmission quality due to bad instantaneous channel conditions. On the other hand, scheduling for wireless mesh networks has drawn a lot of research attention recently. Due to the fact in [2] and [12] that finding a perfect match with the highest network throughput is NP-complete ([10], [3]) for centralized scheduling algorithms, various distributed scheduling algorithms were proposed. Recently, [4] and [5] proposed a distributed opportunistic scheduling algorithm for backhaul networks, which provides multi-user diversity gain in the wireless environments, enforces resource allocation in the long run and maintains strong temporal correlation for interference, without which channel quality and interference cannot be tracked and predicted with reasonable accuracy.

In this paper, we propose a novel cross-layer framework that combines a QoS routing scheme with a distributed opportunistic scheduling algorithm for wireless mesh networks. Our contribution is threefold: (1) we provide a unified approach to integrate multiple QoS constraints in a sole utility function, (2) we exploit the multiuser diversity gain and multiple antenna directive gain, (3) we successfully combine three different layers (i.e., network, MAC and PHY).

More specifically, this work is an extension of the integrated QoS routing (*IQoSR*) protocol presented in [9]. The actual interface between the scheduling and routing schemes is defined and a novel utility function is used to link the and-to-end and long term routing demands with the short term and localized scheduling decisions of the opportunistic scheduling scheme [5] under consideration. Directional antenna transmissions with adaptive modulation schemes have been considered in the physical layer while channel prediction in different time-scales is included to assist and guide the optimum operation of the overlying layers and algorithms. Extensive simulation results show that our algorithms can successfully guarantee multi-constrained QoS while at the same time achieving better network performance compared with other standard techniques. Moreover, the impact of the resource reservation weight factor β, defined in [9] and its effect on the QoS outage probability and blocking probability of new flows is investigated and analyzed.

The rest of the paper is organized as follows. In Section II, the system model and the algorithm description are introduced. Section III provides a thorough description of the cross-layer framework and the interface between scheduling and routing schemes. Numerical results and a detailed performance analysis are given in Section IV. Finally conclusions are drawn in Section V.

II. System Model & Algorithm Description

Consider a wireless mesh network comprises a set of n_r number of WMRs, denoted as $V_R = \{v_r | r = 1, 2, \ldots, n_r\}$ and a set of n_g number of IGWs denoted as $V_G = \{v_g | g = 1, 2, \ldots, n_g\}$. Each WMR independently generates data sessions. Each QoS flow with flow index q has to fulfil a set of QoS constraints that includes ETE packet delay D_q^r, throughput T_q^r and packet-error-rate (PER) E_q^r. We denote this set as (D_q^r, T_q^r, E_q^r). A route Ω_{st}^k from a source WMR with index s to a destination IGW indexed t within the route set Ω_{st} is concatenated by a set of links $\{(v_i, v_j)\}$, for all $v_i, v_j \in V_R \bigcup V_G$. Therefore, we could formally express the route from s to t as (1), where total m candidate routes exist. In the following discussions, we use term session and flow for the traffic input, (v_i, v_j) and (i, j) for the link between v_i and v_j interchangeably.

$$\Omega_{st}^k = \{(v_i, v_j) | \forall v_i, v_j \in V_R \bigcup V_G, k = 1, 2, \ldots, m\} \quad (1)$$

A. QoS Performance Metric

As it has been mentioned above the problem of providing optimum routes that guarantee multiple QoS constraints has been proven to be NP-complete [13]. Therefore, in order to overcome this difficulty we define a new utility function based on the "dissatisfaction ratio" $\mathcal{R}$ that experienced by each QoS metric. More specifically, we define the ratio $\mathcal{R}$ for each of the QoS requirement as follows:

1) $\mathcal{R}_k^D$: ETE packet delay dissatisfaction ratio for route Ω_{st}^k is defined as the actual delay measurement, $\sum_{(i,j)\in\Omega_{st}^k} D_{ij}^a$, over the QoS delay requirement D_q^r,i.e.,

$$\mathcal{R}_k^D(q) = \frac{\sum_{(i,j)\in\Omega_{st}^k} D_{ij}^a}{(1-\beta_D) D_q^r}. \quad (2)$$

2) $\mathcal{R}_k^T$: Throughput dissatisfaction ratio is formulated as the ratio between the throughput requirement T_q^r and actual *bottleneck* link throughput, $\min_{(i,j)\in\Omega_{st}^k} T_{ij}^a$, the minimum of

TABLE I
QoS FLOWS WITH RELATED RESOURCE RESERVATION FACTORS

	voice-over-IP	**Interactive-video**	**Broadband Data**
$\mathcal{I}_D, \beta_D$	1, *changeable*	1, *changeable*	0, —
$\mathcal{I}_T, \beta_T$	1, *changeable*	1, *changeable*	1, *changeable*
$\mathcal{I}_E, \beta_E$	0, —	1, *changeable*	1, *changeable*

all one-hop throughputs along route Ω_{st}^k, i.e.,

$$\mathcal{R}_k^T(q) = \frac{(1+\beta_T)T_q^r}{\min_{(i,j)\in\Omega_{st}^k} T_{ij}^a} \tag{3}$$

3) $\mathcal{R}_k^E$: PER dissatisfaction ratio is defined as the multiplication of all one-hop error rate, $1-\prod_{(i,j)\in\Omega_{st}^k}(1-E_{ij}^a)$, over PER requirement E_q^r since this is a multiplicative constrain, i.e.,

$$\mathcal{R}_k^E(q) = \frac{1-\prod_{(i,j)\in\Omega_{st}^k}(1-E_{ij}^a)}{(1-\beta_E)E_q^r} \tag{4}$$

A resource reservation margin factor has been introduced as β_D, β_T and β_E for delay, throughput and PER respectively. In other words β_i represent the additional resources that we reserve beyond the QoS requirements in order to provide a safe guard for imperfect resource estimations and system fluctuations. The impact of β_i on the QoS outage probability and new sessions blockage probability is given in section ???.

Since a session has to fulfil the set of QoS requirements, a source-to-gateway route will be feasible if and only if all defined ratios are less than one $(\mathcal{R}_k^D(q), \mathcal{R}_k^T(q), \mathcal{R}_k^E(q)) \le 1$. However, some constraints may not be critical in some applications (for instance, broadband data services are not sensitive in delay). In order to efficiently cope with this issue we introduce the indication function $\mathcal{I}_p$, where $p = D, T, E$, expressed as

$$\mathcal{I}_p = \begin{cases} 1 & \text{if parameter } p \text{ is critical in QoS flow } q \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

An example of the resource reservation margin factors and indication functions chosen for three types of QoS flows in the network, namely, voice-over-IP, interactive-video and broadband data services respectively, is demonstrated in Table I.

Our multi-constrain performance index in route Ω_{st}^k can be formulated as

$$U_k = \max[\mathcal{I}_D\mathcal{R}_k^D(q), \mathcal{I}_T\mathcal{R}_k^T(q), \mathcal{I}_E\mathcal{R}_k^E(q)] \tag{6}$$

and the proposed multi-objective function in order to take an optimum heuristic decision is given by

$$\mathcal{S} = \min_{\forall\Omega_{st}^k\in\Omega_{st}} [U_k] \tag{7}$$

III. CROSS-LAYER FRAMEWORK

This section provides a thorough description of the interactions and interfaces between different layers and the layered parameter and functionalities that have been taken into account in our proposed framework.

PHY Layer: The Jake's Model [6] is used for the wireless channel representation while the required PER is derived based on SINR curves for the used adaptive modulation and coding scheme. Each WMR is equipped with directional antennas while accurate positioning is assumed.

At given time t, the receiving SINR γ_{ij} for the transmitter-receiver pair (v_i, v_j) is given by (8),

$$\gamma_{ij} = \frac{P_{ij}C_{ij}d_{ij}^{-\alpha}}{\sum_k P_{kj}C_{kj}d_{kj}^{-\alpha} + \mathcal{N}_0} \tag{8}$$

where P_{ij}, C_{ij} and $d_{ij}^{-\alpha}$ are transmission power, channel gain (the antenna gain has been also included here) and path loss between link (v_i, v_j) respectively. Typical value for path loss exponential factor is 3.5. $\mathcal{N}_0$ is the single-sided power spectrum density for additive white Gaussian noise.

In order to reduce the interference to adjacent concurrent transmissions and increase the frequency reuse and channel capacity, the WMRs are equipped with directional antennas. Furthermore, half duplex is assumed and power control is not considered in this phase, i.e., all the nodes have the same fixed transmission power.

Medium Access Control: In order to exploit the multi-user diversity gain, the distributed opportunistic proportional fair scheduler proposed in [4][5] is considered in our cross-layer framework. This scheduling scheme has been proven not only to achieve a network throughput improvement but at the same time to allow for more accurate channel predictions by providing high level of temporal correlation of interference. This property is of paramount importance for the long term prediction of channel quality required for the optimum performance of the routing algorithm as it will be described in the following.

However, the opportunistic nature of this scheme comes with the inherent difficulty to guarantee the required QoS performance in a long run. This is because opportunistic approaches usually introduce more fluctuating instantaneous performance at individual nodes. In order to overcome this a utility function (or scheduling metric) that comprises both routing and scheduling parameters is used. In that way not only it achieves opportunistic gain but also supports quality of service as committed by the routing algorithm in use.

The routing algorithm estimates the routing demand for the session q in a certain future (e.g., for the whole duration of a data session) and passes the scheduling the throughput allocation target a_{ij}^q for the link (i,j). For instance, the routing algorithm may ask for $a_{ij}^q = (1+\beta_T)\cdot T_q^r$ amount of bandwidth resources to be reserved on the link (i,j). The scheduling scheme at node i will generate the throughput allocation target vector $\overrightarrow{a_i} = (a_{i1}, a_{i2}, ..., a_{il})$ with the demands of all l incoming and outgoing links and activate the appropriate link for transmission-reception each time based on the following utility function,

$$U_{ij} = a_{ij}^q \frac{\rho_{ij}}{C_{ij}} \tag{9}$$

where ρ_{ij} and C_{ij} are the instantaneous throughput and channel capacity in the long run respectively. [5] proves that, from a MAC perspective, by choosing the proposed link utility

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Channel Model	Jakes Model	Path Loss Coeff.	2-4
Antenna Pattern	Side lobe: -25dB Main lobe: 30°	AMC	MPSK MQAM
Doppler Freq.	10-25Hz	System Bandwidth	50MHz
Slot Duration	80us	Slots per Frame	100
Frame Duration	8ms	Packet Length	512 bytes
WMR	15	IGW	1
Network Size	3 miles	Tx Range	1.5 miles
Traffic Arrival	Poisson		

metric (9) the scheduler guarantees the proportional target QoS throughput as well as fairness among links. However, in this paper it is not clear how the localized and short term scheduling decisions can affect the long term routing performance and guarantee the multiple QoS requirements.

Performance parameters prediction: The performance of the proposed framework highly depends on the accurate estimation of multiple system parameters required for the optimum routing decision. For this reason, each node keeps a table with measurement of previous transmissions from all its neighbors. The measured parameters include link throughput, Signal-to-Interference-plus-Noise-Ratio (SINR) and queuing delay. The throughput statistics are passed to the scheduling scheme for the estimation of the long run channel capacity C_{ij}. The SINR statistics for each link (i, j) and the queuing delay statistics in each node are used to estimate the expected PER and ETE packet delay, respectively, for the routing decisions.

IV. NUMERICAL RESULTS

To access the cross-layer framework performance a slotted, time-driven simulation platform has been developed. A number of WMRs and IGWs are randomly and independently deployed on a rectangular two-dimensional space. Sessions are generated according to a Poisson process. Each session has to fulfil three QoS constraints, i.e., ETE packet delay, throughput and end-to-end PER. Retransmission scheme is assumed in case of packet failure. The simulator includes the PHY, MAC and Network aforementioned algorithms as they have been described in the previous sessions. The simulation parameters are summarized in Table II.

For comparison purposes, the well known Round Robin (RR) scheduler [14] and the AODV routing protocol are used as benchmarks and four different combinations are considered as they summarized in Table III. This gives as the opportunity to investigate separately the impact of scheduler and routing algorithm on the performance of our system.

The performance of the proposed cross-layer framework is investigated in terms of Gateway Throughput (Fig. 2a) and probability of successful end-to-end packet reception as a function of the packet inter-arrival time. The probability of success is defined as the ratio of the packets that arrive at the gateway and have fulfilled the Delay QoS requirements (Fig. 2b), denoted as P_D^S, and the PER QoS requirements (Fig. 2c), denoted as P_{PER}^S, throughout the whole route.

TABLE III
FOUR COMPARISONS

	MAC Scheduling	Routing	Cross-Layer Term
1	Round Robin	AODV	RR/AODV
2	Round Robin	IQoSR	RR/IQoSR
3	Distributed Opportunistic	AODV	Dist/AODV
4	Distributed Opportunistic	IQoSR	Dist/IQoSR

Fig. 2a shows that the opportunistic scheduler considered in our framework can guarantee hight throughput even for small inter-arrival rate when the offered network traffic is getting high. On the other hand, the RR scheme provides a constant throughput since the channel resources are reserved (on MAC level) independently of the offered traffic. The combination of opportunistic scheduling and our proposed routing scheme gives by far the best overall performance.

Fig. 2b highlights the fact that our proposed framework can also satisfy the packet delay QoS requirements while at the same time guarantees high throughput rate at the gateway side. It is interesting to note that the outage probability is less than 0.1 even for high traffic conditions. However, the PER probability is much worst compared to the three other cases as it can be seen from Fig. 2c. Nevertheless, the dominant effect for the end-to-end packet delay is the queuing delay in each node's buffer and that gives to our framework better overall delay performance.

Fig. 3 depicts the outage probability of QoS per session as a function of the resource reservation weight factor β. This is defined as the probability of any of the QoS requirements of a session to fail during the life time of the given session. In other words, it gives the probability of $U_k(q) > 1$. For simplicity we assumed the same β for each QoS metric, i.e., $\beta_D = \beta_T = \beta_E = \beta$ and the inter-arrival time of new flows is set to 6ms. It is important to notice that even for $\beta = 0$ (i.e., we do not reserve any additional resources) our proposed distributed QoS routing algorithm integrated with the opportunistic scheduler can guarantee the all the QoS of the underlying application for 88% of the time compare to 78% if round robin is used for scheduling. Generally it can be seen that the used utility function (9) for the opportunistic scheduler can guarantee around 10% lower outage probability than the round robin independent of the additional resources requested by the router. By increasing the resource reservation weight factor we can reduce the outage to less than 5% (i.e., for $\beta > 0.3$), however this means that more resources are reserved per session affecting in this way the admission rate of new incoming flows.

This trade-off becomes clearer in Fig. 4 where the effect of β on the blocking probability of new incoming sessions is demonstrated. It can be seen that a less than 5% outage probability for existing flows comes with the cost of more than 25% blocking probability for new flows. Nevertheless, by using the proposed utility function (9) together with our multi-constrain QoS routing scheme, we can achieve 10% blocking probability compare to the case where round robin is used.

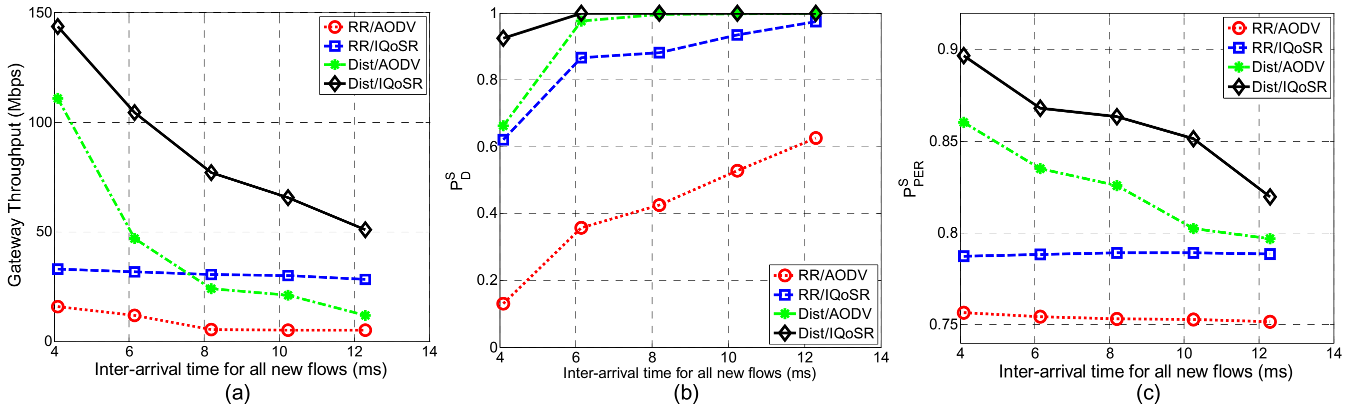

Fig. 2. The effect of network traffic on (a) Network Throughput, probability of successful end-to-end packet reception in terms of (b) Packet Delay and (c) PER.

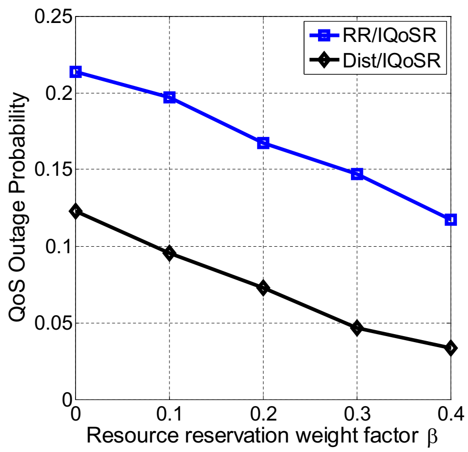

Fig. 3. QoS outage probability for existing sessions.

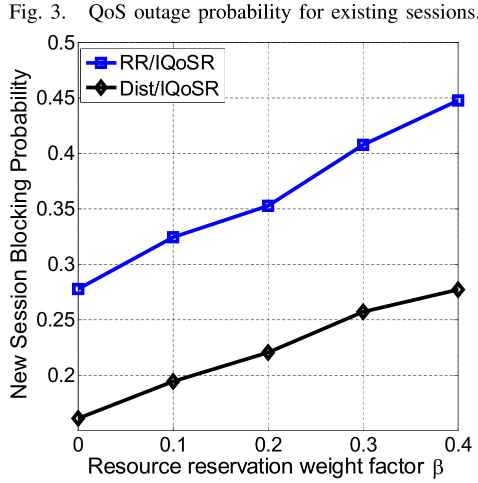

Fig. 4. Average blocking probability for new incoming sessions.

V. Conclusions

In this paper, a novel cross-layer QoS routing and distributed opportunistic scheduling framework for wireless mesh networks has been proposed to provide multiple QoS guarantees by resource reservation and allocation schemes. Extensive simulation results shows that by careful consideration of the resource reservation weight factor β, our proposed framework achieves higher network performance gain and better QoS guarantees in comparison to other benchmark protocols. Moreover, the proposed integrated QoS performance metric can be easily extended to other metrics like delay jitter or user-defined utilities, and used for multi-path routing. Future research will include investigation of the joint QoS routing and scheduling optimization problem using directional antennas and MIMO techniques in the PHY layer.

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