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# A Novel Direction-of-Arrival Estimation Algorithm for WCDMA

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## Abstract

Despite the controversies that surround the introduction of the third generation (3G) mobile telecommunication systems, the massive investment by industry and the constant demand for new technology and services are expected to usher in its eventual success. WCDMA is a dominant standard in the 3G system designed to succeed the highly successful GSM standard. A new technology proposed for WCDMA is adaptive antennas. Among the challenges involved in the technology are downlink beamforming and mobile user localization whereby a reliable direction-of-arrival (DOA) estimation algorithm could form part of the solution. In this paper, we propose a simple single-user approach to perform DOA estimation in WCDMA that is based on a well known space-time (2-D) rake receiver for uplink reception. We show that by incorporating some additional knowledge of the signal environment, promising improvement can be obtained. The algorithm is tested under the realistic COST259 channel model to further substantiate our claim.

## 1 Introduction

The long awaited rollout of WCDMA services in Japan in Oct 2001 marked the beginning of third generation mobile telecommunications services. Even though the initial consumer response did not match the industry's optimism, major telecommunication companies around the world are going ahead with their plans to introduce the new system. Aside from the pressure to recover the many billions of US dollars already invested into research and the purchase of spectrum licenses and equipment, the companies recognize the vast potential of the system in providing new revenue-generating services. The search is currently on for a killer application to encourage quick and widespread adoption of the technology.

The development and rollout of WCDMA also pose a new set of difficult technical challenges to engineers, as is clear from the recent Japanese experience. In comparison with second generation systems, WCDMA is much more advance in technology, and thus far more difficult to

implement and maintain. Issues such as system capacity and quality of service will become increasingly important as the systems grow. The maturing adaptive antennas system (AAS) technology is favored to play an important role in the future enhancement and development of WCDMA systems [1].

The use of AAS in mobile telecommunications has received significant attention in recent years [1], [2], [3]. Commercial products incorporating the technology, such as Ericsson's RBS2205, are already available. The main advantage of AAS lies in its ability to exploit the spatial characteristics of the mobile channel to improve the reception of mobile signals. WCDMA systems, in particular, are inherently suitable for AASs because the capacity of CDMA systems is soft-limited by interference level and any suppression of interference would provide an instant capacity increase [1].

Currently, there exist a few different types of AAS architectures, ranging from the simple fixed multi-beam AASs for both uplink and downlink, to the fully-steerable beam AASs for downlink and combined spatial/temporal interference cancellation for uplink [4]. For steerable beam AASs, an explicit estimation of the directions-of-arrival (DOA) of the signals of interest is required for downlink beamforming since the use of frequency division duplex (FDD) mode in WCDMA renders the use of estimated array weights based on uplink spatial signature ineffective for downlink beamforming [5]. Moreover, DOA is also important for emergency services and other radiolocation applications [6].

In this paper, we are concerned with the single-user approach to DOA estimation for WCDMA using uniform linear arrays (ULAs). In particular, we are interested in techniques that make use of information available to the AAS, e.g. [7], [8]. We propose a simple DOA estimation algorithm with an aim to *reuse* as much as possible the decoupled 2-D rake receiver structure in [9]. In essence, we make use of the pilot sequence and the root raised cosine (RRC) chip waveform in the Dedicated Physical Control Channel (DPCCH) [10] on top of the known desired user code in order to improve on the estimate of the desired signal covariance matrix. This improvement results in smaller biases and standard deviations in the DOA estimates caused by the non-whiteness of multiple

access interference (MAI). We also apply an estimate of the MAI-and-noise covariance matrix to whiten the signal-MAI-noise covariance matrix and show that a further improvement can be obtained. Among the benefits of this approach is that the number of array elements no longer limit the number and proximity of identifiable signal paths [7]. In fact, different users with the same DOA can be identified.

In this paper, we despread the received WCDMA signal and use Root-MUSIC [11] on the despread covariance matrix for DOA estimation. Many other DOA estimation techniques may be similarly applied to the covariance matrix, e.g. Root-WSF or MODE [12], or ESPRIT [3]. In the simulation study, we demonstrate the performance of our method in dynamic (with user mobility) simulations by the use of the realistic COST259 channel model [13]. We show that our method can significantly outperform the conventional approach.

## 2 WCDMA Uplink Signal Model

Here we give a summary of the WCDMA signal model [9], [10], [14]. The user data in WCDMA is carried on the Dedicated Physical Data Channel (DPDCH). More than one DPDCH may be multiplexed onto the in-phase (I-) and quadrature-phase (Q-) channels. The DPDCHs on each of the I- and Q-channels uses different orthogonal variable spreading factor (OVSF) codes for channelization. The spreading factor used in the DPDCHs differs according to the desired data rate. Each user also has a DPCCH with a constant spreading factor of 256 that is mapped onto the Q-channel. For DPCCH, one radio frame has 15 slots and each slot has 10 bits. The number of pilot bits is  $N_p \in [3, \dots, 8]$  [10]. The DPDCHs with lower spreading factor (higher data rates) are allocated higher amplitude gains. The amplitude gain factors are:  $\beta_D$  for DPDCH, and  $\beta_C$  for DPCCH. In this paper, we consider only one DPDCH on the I-channel and one DPCCH on the Q-channel. In Fig. 1, we show the block diagram for uplink spreading.

The baseband representation of DPDCH [9] is

$$s_D(t) = \sum_{k=-\infty}^{\infty} b_D^{(k)} z_D(t - kT_D) \quad (1)$$

$$\text{where } z_D(t) = \sum_{h=1}^{Q_D} c_D^{(h)} p(t - hT_c), \quad (2)$$

$T_D$  is the symbol period of the data on DPDCH,  $T_c$  is chip period corresponding to the WCDMA chip rate of  $3.84 \times 10^6$  chips/s,  $c_D^{(h)} \in \{\pm 1\}$  is the  $h$ th chip of the OVSF spreading code,  $b_D^{(k)} \in \{\pm 1\}$  is the  $k$ th data symbol and  $p(t)$  is the impulse response of the RRC pulse shaping filter for the chip waveform on WCDMA. The roll-off factor of  $p(t)$  is  $\alpha = 0.22$ . Similarly, the baseband representation of DPCCH is

$$s_C(t) = \sum_{k=-\infty}^{\infty} b_C^{(k)} z_C(t - kT_c), \quad (3)$$

$$\text{where } z_C(t) = \sum_{h=1}^{Q_C} c_C^{(h)} p(t - hT_c), \quad (4)$$

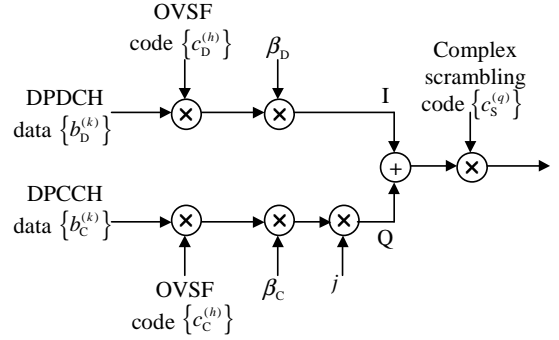


Fig.1. Block diagram for uplink spreading

and  $b_C^{(k)}$ ,  $c_C^{(h)}$ ,  $T_c$  and  $Q_C$  follows the notations of the DPDCH case.

The DPDCH and DPCCH are then appended onto the I- and Q-channels respectively of the transmitted QPSK signal. The complex scrambling code of length  $Q_S = 38400$  chips (length of one radio frame) is also added. The scrambling code is aligned with the start of each radio frame. The transmitted baseband signal of the  $i$ th user equipment (UE) is then

$$s_i(t) = \left[ \sum_{r=-\infty}^{\infty} s_s(t - rT_f) \right] \times [\beta_D s_D(t) + j\beta_C s_C(t)], \quad (5)$$

$$\text{where } s_s(t) = \sum_{q=1}^{Q_S} c_s^{(q)} p_{T_c}(t - qT_c), \quad (6)$$

$$\text{and } p_{T_c}(t) = \begin{cases} 1, & 0 \leq t < T_c \\ 0, & \text{elsewhere} \end{cases} \quad (7)$$

$c_s^{(q)} \in \{\pm 1 \pm j\}$  is the  $q$ th chip of the complex scrambling code and  $T_f = Q_S T_c = 10$ ms.

The AAS of interest is a  $N$ -element ULA with inter-element spacing  $d$  and operating wavelength  $\lambda$ . For  $M$  UEs where  $M = 1$  is the desired UE, the continuous time signal at the array output after the receiver RRC filter can be written as follows:

$$\mathbf{x}(t) = \sum_{\ell=1}^{L_1} \rho_{1\ell} \mathbf{a}(\theta_{1\ell}) s_1(t - \tau_{1\ell}) \otimes p(t) + \sum_{m=2}^M \sum_{\ell=1}^{L_m} \rho_{m\ell} \mathbf{a}(\theta_{m\ell}) s_m(t - \tau_{m\ell}) \otimes p(t) + \mathbf{n}(t) \quad (8)$$

where  $\otimes$  denotes the convolution operation,  $\theta_{m\ell}$ ,  $\rho_{m\ell}$ , and  $\tau_{m\ell}$  are respectively the DOA, complex gain and delay of the  $\ell$ th path of the  $m$ th UE,  $L_m$  is the number of signal paths of the  $m$ th UE,  $\mathbf{n}(t) = [n_1(t), \dots, n_N(t)]^T$ ,  $n_\eta(k)$ 's are complex i.i.d Gaussian noise with power  $\sigma_N^2$ , and  $\mathbf{a}(\theta_{m\ell}) = [a_1(\theta_{m\ell}), \dots, a_N(\theta_{m\ell})]^T$ ,

$$a_\eta(\theta_{m\ell}) = \exp\left(j \frac{2\pi d}{\lambda} (\eta - 1) \sin \theta_{m\ell}\right). \quad (9)$$

Assuming negligible cross-correlation between desired signal and MAI. The covariance matrix is given by

$$\mathbf{R}_{\text{SIN}} = \mathbf{E}\{\mathbf{x}(t) \mathbf{x}^H(t)\} = \mathbf{R}_S + (\mathbf{R}_I + \mathbf{R}_N) = \mathbf{R}_S + \mathbf{R}_{\text{IN}} \quad (10)$$

where  $\mathbf{R}_S$ ,  $\mathbf{R}_I$ ,  $\mathbf{R}_N = \sigma_N^2 \mathbf{I}$  is the desired signal, MAI and noise covariance matrices, respectively.

### 3 Proposed Method

#### 3.1 Oversampling

The use of the pilot sequence (i.e. a known signal) to estimate DOA in CDMA systems is well known [7]. Here, we use an oversampled (of factor  $N_S > 1$ ) and normalized raised cosine (RC) pulse-shaped chip sequence to correlate with the received signal. We aim to recover the part of the signal covariance matrix that contains the direct path desired signal cluster (of local scattering). This is done by cross-correlating the received signal to obtain the time positions of the  $L_{c1}$  largest correlations,  $t_n$ 's. We can then form

$$\mathbf{y}^{(n)} = \sum_{\kappa=1}^{N_E} \mathbf{x} \left( t - t_n - \kappa \frac{T_c}{N_S} \right) \tilde{s}_1^* \left( t - \kappa \frac{T_c}{N_S} \right) \quad (11)$$

where  $N_E = N_p N_S Q_c + \tilde{N} - 1$ , and  $\tilde{N}$  the length of the oversampled RC pulse used,  $\tilde{s}_i(t)$  denotes the RC pulse convolved DPCCH chip waveform of  $i$ th user for the entire length of the known pilot sequence,. Therefore,

$$\hat{\mathbf{R}}_S^{(n)} \approx \frac{1}{N_E} \mathbf{y}^{(n)} \mathbf{y}^{(n)H}, \quad n \in \{1, \dots, L_{c1}\}, \quad (12)$$

where in our simulation study, we consider only one rake finger, i.e. one with the largest correlation.

#### 3.2 MAI Whitening

To perform whitening for the  $n$ th rake finger, we need to estimate  $\mathbf{R}_{IN}$  at that finger, i.e.  $\hat{\mathbf{R}}_{IN}^{(n)}$ . We start with obtaining an estimate of  $\mathbf{R}_{SIN}^{(n)}$  as follows

$$\hat{\mathbf{R}}_{SIN}^{(n)} = \frac{1}{N_E} \sum_{\kappa=1}^{N_E} \mathbf{x} \left( t - t_n - \kappa \frac{T_c}{N_S} \right) \mathbf{x}^H \left( t - t_n - \kappa \frac{T_c}{N_S} \right). \quad (13)$$

When more than one slot are used for DOA estimation, the covariance matrices of all the slots are averaged. From (8) and (10) we can then form

$$\hat{\mathbf{R}}_{IN}^{(n)} \approx \hat{\mathbf{R}}_{SIN}^{(n)} - \hat{\mathbf{R}}_S^{(n)}. \quad (14)$$

We use  $\hat{\mathbf{R}}_{IN}^{(n)}$  to whiten the MAI in  $\hat{\mathbf{R}}_{SIN}^{(n)}$ . The resulting  $\hat{\mathbf{R}}_{SIN}^{(n)}$  is then used for DOA estimation. Note that (14) has an exact form for the case of chip rate sampling [9] (not involving  $p(t)$ ), though in [9] it is used for uplink beamforming on a 2-D rake receiver.

### 4 WCDMA Simulator

In this section, we describe the WCDMA simulator developed for the evaluation of DOA estimation.

#### 4.1 Simulator Structure

In the simulator, all UEs generate and transmit continuous data streams that follows the WCDMA radio interface specifications [10]. The long code is used for scrambling. The signals are passed through a COST259 channel and received at a base station (BS) equipped with an AAS. The AAS consists of a ULA where the array outputs are fed into a decoupled 2-D rake receiver [9].

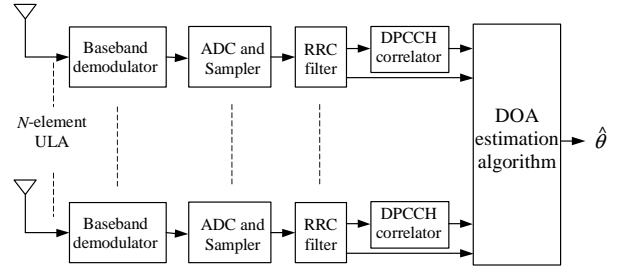


Fig. 2. Block diagram of simulator

The cross-correlation to search for the rake fingers is performed over  $N_S = 2$  oversampled chip data. To model the asynchronous uplink, we assumed ideal sampling time for the desired UE and random sampling instants for the interfering UEs. Fig. 2 shows the block diagram of the parts of the receiver that are relevant to DOA estimation. Note that we do not require any additional information than those available to the 2-D rake receiver with  $N_S = 2$ .

#### 4.2 Simulation Environment

In this study, we investigate a scenario with one desired UE and multiple interfering UEs in the 2GHz frequency band. The base station (BS) is operating in a 120° sector cell and employs a 4-element ULA with  $d/\lambda = 0.5$ . The simulation scenario is illustrated in Fig. 3.

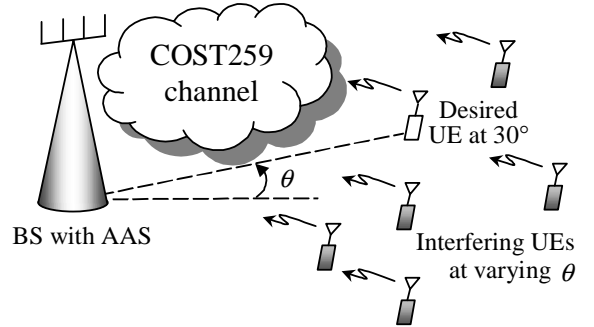


Fig. 3. Simulation scenario: a BS, a desired UE and multiple interfering UEs.

WCDMA uses both open (slow) and closed loop (fast) power control for all active UEs. Therefore, the power discrepancies among the UEs are expected to be small. Here we assume perfect power control such that the channel response of each UE in the system is normalized with respect to the reference antenna (i.e. antenna 1).

#### 4.3 COST259 Channel Model

The COST259 channel model [13] is a versatile channel model devised under the COST259 project of the European Community. COST259 has been validated using measurements in the 1GHz to 2GHz range, but is expected to be applicable at least in the range 450MHz to 5GHz. It is a wideband directional channel model capable of providing channel impulse responses in both spatial (azimuth and elevation) and temporal domains.

Channel type	Parameter		
	Average number of clusters	Typical azimuth spread per cluster (degrees)	LOS cut-off distance (meters)
TU	1.17	10	500
BU	2.18	10	500
RA	1.06	5	5000
HT	2.00	5	5000

Table 1. Examples of COST259 Channel Parameters

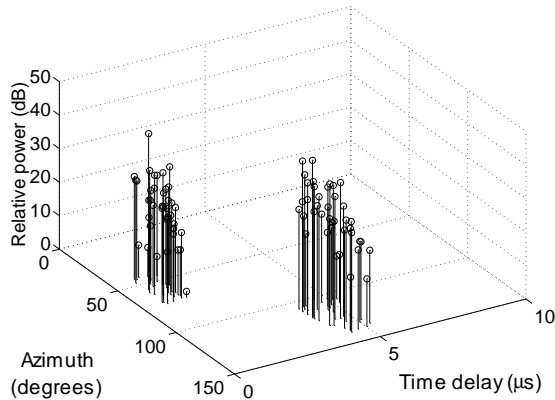


Fig. 4. Example of a BU channel realization with two clusters in the temporal/azimuthal plane.

The COST259 channel model incorporates, among others, the effects of path loss, fast fading and shadow fading. The environment currently implemented is macrocell. The channel types modeled are typical urban (TU), bad urban (BU), rural area (RA) and hilly terrain (HT), which are generalizations of the GSM channel models with the same names. Examples of the parameter settings are given in Table 1. An example of a BU channel realization with two clusters is shown in Fig 4.

## 5 Simulation Studies

In the simulation studies, for each of the COST259 channel types, RA, TU, BU, and HT, and a flat fading (FF) channel, we perform 300 Monte-Carlo experiments where in each experiment the scattering environment and UE distribution is changed. In each experiment, either 5 or 15 slots are used for DOA estimation where each slot contains 6 pilot bits. There are a total of 50 UEs: the desired UE (speech user) is situated at  $30^\circ$  and 250m from the BS while the 49 interfering UEs are randomly placed in the sector between the range 200m and 800m and each UE is moving at 3km/hr along the radial direction. We assume 30 speech users, 10 medium data rate users and 10 high data rate users where  $\beta_v/\beta_c$  of the speech, medium data rate and high data rate users are 1, 3 and 5, respectively. Out of sector MAI and ambient noise are modeled as Gaussian distributed noise. The signal-to-noise ratio (SNR) of each UE after the receiver RRC filter is 20dB. We apply root-MUSIC [11] in all cases for DOA estimation.

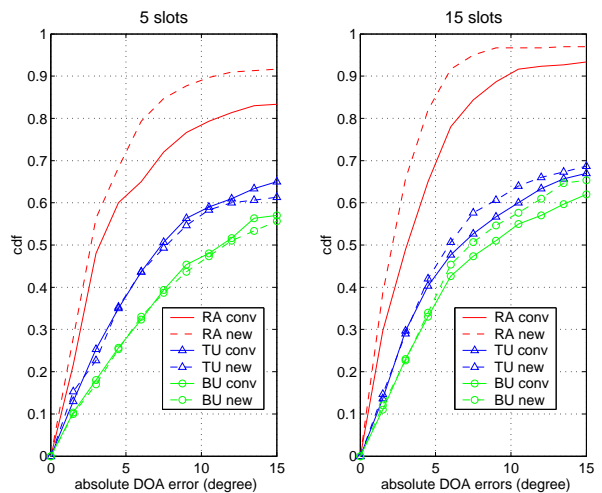


Fig. 5. Cdfs of absolute DOA error for RA, TU and BU

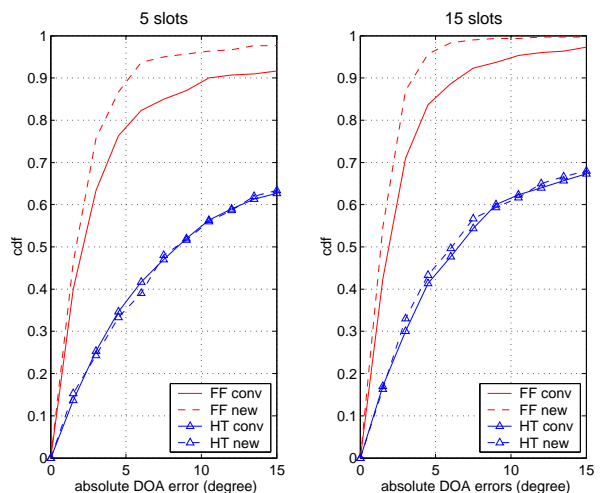


Fig. 6. Cdf of absolute DOA error for FF and HT

In the channel types considered, some experiments failed completely to locate the DOA of the desired UE and statistical measures such as mean and standard deviation are unsuitable for performance evaluation. Instead, the results are presented in terms of the cumulative distribution functions (cdf) of the absolute DOA estimation errors. Fig. 5 shows the results for RA, TU and BU for 5 and 15 slots and Fig. 6 shows the results for FF and HT. “conv” denotes the conventional method of using the desired UE chip waveform (over the pilot length) at chip rate to despreading the received signal, i.e.  $N_S = 1$  for (11)-(12) with  $N_E = N_p Q_C$ .  $\hat{\mathbf{R}}_S^{(n)}$  is then used for DOA estimation. “new” denotes the new method with oversampling (for cross-correlation) and whitening, i.e. applying  $N_S = 2$  to (11)-(14).

It is clear that in all cases, the use of more slots improves the DOA estimation. This gain is due to the slowly changing channel response for the UE speed of 3km/hr. In Fig. 5 and 6, we note that the performance of the new method is particularly promising in FF and RA. If we set the performance benchmark at  $5^\circ$  absolute error (in view of the beamwidth of ULA), the correctly resolved DOAs in both FF and RA are improved by 12% for 5

slots, and 10% and 15% respectively for 15 slots. This is unsurprising since FF only has one line-of-sight (LOS) direct path and the one rake finger used is able to rake up all the desired signal power. The oversampling procedure provides more samples (and information) to the cross-correlation of (11) and thus improves the averaging process. This then reduces the level of MAI. Moreover, a good desired signal estimate also enable a good estimate of the MAI for whitening. Therefore, both oversampling and whitening procedures are effective. Likewise, RA has a high probability of LOS in the given scenario. It also has small angular and temporal spreads (see Table 1) that ensure a good estimate of the desired signal based on one rake finger.

For TU, BU and HT, performance differences are less well defined within the range of interest (at around absolute DOA error of  $5^\circ$ ), with some cases giving marginal improvements (e.g. BU for 15 slots) while other cases only give similar performances to that of the conventional method. This is because of the significant angular and temporal spread for TU, BU and the high probability of non-LOS (NLOS) (see Table 1 and Fig. 4). In NLOS cases, even though the signal cluster of the local scatterers are still contained in a region around the nominal DOA, it has a smeared out energy spread in both the spatial and temporal domains. For the rake receiver, any signal path that is more than a sampling period from the rake finger of interest produces a virtual interfering UE. Also while HT has small angular and temporal spreads for each cluster and high LOS probability, it has a high probability of having two or more signal clusters. Once again, this smears out the energy and degrades the performance of one rake finger. A further challenge in these environments is the time-varying asymmetrical angular spread about the nominal DOAs. As such, many existing work on DOA in scattering environment cannot be applied as the focus is on symmetrical scattering sources and sources with a known angular distribution.

In view of these observations, we note that some improvements are expected especially for complex scattering environments, e.g. BU, if we take a few more rake fingers into account. Nevertheless, care is required in the choice of rake fingers due to the frequent occurrence of more than one strong signal clusters in BU and HT where the DOAs of these clusters are significantly different from the nominal DOAs of the desired UE. Another interesting aspect for further work is the impact of non-ideal power control (residual "near-far problem").

## 5 Conclusions

The introduction of WCDMA presents many exciting technical challenges. Among them is the application of AAS technology in which DOA estimation plays an integral part. Apart from identifying user direction for downlink beamforming, it can also provide services on wireless communication networks such as public safety and enhanced emergency services, location sensitive billing, vehicle and fleet management, fraud detection, and Intelligent Transport Systems (ITS). In this paper, we

proposed a technique that can be used to improve a simple single-user approach to DOA estimation in WCDMA. In the simulation studies, we showed that the new method gives promising gains over the conventional method under favorable environments and experiences no noticeable degradation in challenging environments.

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