Temporal Cognitive UWB Medium Access in the Presence of Multiple Strong Signal Interferers

Thomas Zasowski, Frank Althaus, and Armin Wittneben
Swiss Federal Institute of Technology (ETH) Zurich
Communication Technology Laboratory, Sternwartstrasse 7, 8092 Zurich, Switzerland
Email: {zasowski, althaus, wittneben}@nari.ee.ethz.ch

***Abstract*— To enable reliable transmission, UWB receivers have to cope with interference from several existing wireless services. Based on spectrum analyzer measurements we will show that stationary or quasi-stationary noise can be handled using a high pass filter. For a *narrowband interferer* (NBI) in close vicinity such a filtering is not sufficient since the receiver may be clipping. This can happen especially in wireless *body area networks* (BAN) where a number of different NBIs are placed in close vicinity to the UWB receiver. Since most NBIs transmit their data burst-wise, as, e.g., GSM or Bluetooth (BT), we propose UWB transmission between adjacent interferer bursts to avoid the UWB receiver's clipping. Based on extensive time domain measurements where GSM, BT, and IEEE 802.11b WLAN are all active at the same time, it will be shown that reasonable data rates can be achieved and that strict latency time requirements can be met with such a *temporal cognitive medium access*.**

I. INTRODUCTION

Since the approval of UWB transmission for communication purposes by the FCC [1], UWB coexistence and interference issues are very important. Up to now, most investigations of coexistence issues concern the interference of UWB devices on existing services, e.g. [2], [3]. There exist also some publications considering the impact of existing system's interference on UWB systems, as, e.g., [4], [5]. But only in few publications, e.g., in [6], [7], interference mitigation techniques are considered.

General interference mitigation methods, which are not limited to UWB only, are presented in [8]. There, collaborative and non-collaborative coexistence mechanisms are proposed. In the collaborative scenario, different wireless systems are able to share information and negotiate channel access. In the non-collaborative scenario, different systems do not have the ability to coordinate their transmission. There, wireless systems can use only strategies as, e.g., carrier sense multiple access (CSMA) or adaptive frequency hopping. The disadvantage of such strategies is that the channel is not used to its maximum efficiency. But since existing services are usually not collaborating we consider the non-collaborative approach as more promising for UWB systems and use it as basis for our considerations.

In this paper, we consider two types of interference, which we refer to as *background interference* and *burst interference*. We use the term background noise for stationary or quasi-stationary noise. With this definition, also signals from GSM basestations are considered as background noise since they are transmitting almost continuously. The term burst interference is used for NBIs that transmit their data burst-wise, as, e.g., GSM mobiles.

Based on spectrum analyzer measurements we show that GSM and UMTS basestations are the most critical background noise sources. Such interference can be handled by a UWB receiver using a high-pass filter or antennas, whose frequency transfer functions show strong out-of-band attenuation. Unfortunately, such a mitigation method is not suited if a NBI burst interferer is transmitting in close vicinity to a UWB device and interference becomes too large. Then, the UWB receiver suffers from clipping and no UWB transmission is possible. To avoid this effect we propose a UWB transmission in the time between adjacent interfering bursts where the channel is not occupied. Since not all NBIs, e.g., IEEE 802.11b, exhibit a deterministic burst structure, NBI signals are measured with a real-time sampling oscilloscope in time domain.

Finally, an expression for the achievable pulse rate, which directly translates into throughput, is given and an expression for the optimum UWB packet length is derived. Based on a BAN scenario, where one GSM, one Bluetooth (BT) and one WLAN transmission are active at the same time, we show that a reasonable UWB pulse rate can be achieved with this avoidance strategy. Investigating the UWB packet delays, it is shown that such an interference avoidance method is also suited for applications with strict latency time requirements.

II. BACKGROUND NOISE AND LINK BUDGET

Due to their large bandwidth, UWB devices do not have to cope with thermal noise only but also with a number of different noise sources. Therefore, stationary and quasi-stationary noise, which are almost permanently present, were measured. We refer to stationary and quasi-stationary noise as background noise. One quasi-stationary noise source are ,e.g., GSM basestations. Although GSM basestations transmit their signals burst-wise, they are almost permanently present since such basestations are transmitting to several mobile stations. Background noise measurements were performed in frequency domain using a Skycross SMT-3TO10M antenna connected to a spectrum analyzer. The antenna characteristics is calibrated out from the measurements. The resolution bandwidth was chosen to be 30 kHz. Since the frequency resolution for the whole measured frequency range is limited by the number of measurement points of the spectrum analyzer, we increased frequency resolution by doing subsequent measurements of 20 MHz sub-bands. An overview on the interfering services,

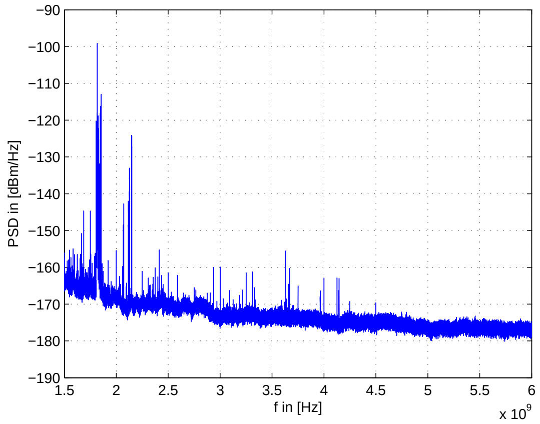

Fig. 1. Background noise averaged over measurements on different day times

which can be observed in Fig. 1, is given in Table I. Not using an additional high pass filter, an interference noise power of

$$N_\text{I} = \int_{1.5\text{GHz}}^{6\text{GHz}} \text{PSD}(f)df \approx -45\text{dBm} \tag{1}$$

is present. This background noise power is dominated by interference from GSM and UMTS base stations, which can be seen in Fig. 1.

Frequency range [MHz]	Service
1805 - 1880	GSM
2110 - 2170	UMTS
2400 - 2500	ISM
2700 - 3400	Radionavigation
3600 - 4200	Fixed wireless services

TABLE I
INTERFERING SERVICES OBSERVED IN BACKGROUND NOISE MEASUREMENTS

For the link budget considerations we assume a UWB transmission in the FCC peak power limit [1]. The peak power limit is defined by a maximum transmit power spectral density of

$$PSD_{\text{TX},50} = 0\text{dBm}/50\text{MHz}, \tag{2}$$

allowing a maximum pulse repetition rate of 1 MHz. Moreover, we consider for the link budget a path loss $PL = 60$dB, which corresponds approximately to a line-of-sight (LOS) link of 5 meter distance [9]. This distance is reasonable for *extended wireless body area networks* (WBANs). There, different from usual WBANs [10] one node is placed close to the body and the other node is located in short distance, but not necessarily on the body. Assuming no further losses due to antenna mismatch or imperfect components the receive power spectral density is then given by

$$PSD_{\text{RX},50} = -60\text{dBm}/50\text{MHz}. \tag{3}$$

Using the background noise power from (1) and the minimum required UWB bandwidth $B = 500$MHz, i.e., $P_{\text{RX},500} = -50$dBm, the signal-to-noise ratio reduces to

$$\text{SNR}_\text{BN} = \frac{P_{\text{RX},500}}{N_\text{I}} \approx -50\text{dBm} + 45\text{dBm} = -5\text{dB}, \tag{4}$$

which is about 30dB below an SNR where only thermal noise is considered. From (4), it can be seen that the achieved SNR is not large enough for reliable communication and that especially GSM and UMTS interference has to be mitigated. This can be done either by applying an antenna whose transfer function has steep slopes or an additional high pass filter that attenuates out-of-band interferers.

Butterworth high pass filters of different orders are considered to determine the impact of filtering on the interference. Since a UWB device should be as simple as possible for BAN applications and since the path loss increases with increasing frequency, the desired frequency band should be located on the lower end of the UWB spectrum. Considering the FCC allowed UWB frequency range $3.1 - 10.6$ GHz, we choose the lower 3dB cut-off frequency of the Butterworth filter as $f_l = 3.1$GHz. In Table II, background noise powers based on the interference measurements from $1.5 - 6$GHz are shown for different filter orders. With increasing filter order a reduction of the noise power and a simultaneous SNR increase can be observed. Using a 5th order Butterworth high pass the noise power is about 6 dB higher than noise power for thermal noise, only. Note, that the desired signal is also attenuated by the filter in the pass band range. But this attenuation does not exceed 3dB.

Filter order	1	2	3	4	5
Noise power [dBm]	-54.2	-58.4	-62.9	-67.3	-71.3

TABLE II
BACKGROUND NOISE POWER FOR BUTTERWORTH HIGH PASS FILTERS OF DIFFERENT ORDERS

III. INTERFERERS IN CLOSE VICINITY

In the previous section it was shown that background noise can be handled by a UWB receiver with high pass filter. But this holds only for interfering devices, which are not located in close vicinity to the UWB receiver. If the instantaneous signal power of an interferer is too high, the UWB receiver suffers from clipping and no UWB transmission is possible. For the clipping considerations we assume the receiver model in Fig. 2, consisting of a high pass filter (HPF), a low noise amplifier (LNA), an automatic gain control (AGC) and an analog-to-digital converter (ADC) with 6 bit resolution. We assume that 3 bit will be used for the desired UWB signal while the remaining 3 bit are a reserved for noise and interference, until the receiver suffers from clipping. The HPF does not limit the bandwidth of the noise $w(t)$ but only attenuates background interference. The LNA and the AGC are assumed to be perfect and do not cause any clipping. The AGC amplifies the desired UWB receive signal in such a way that it fits best in the desired

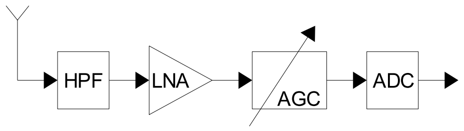

Fig. 2. Receiver model for clipping considerations

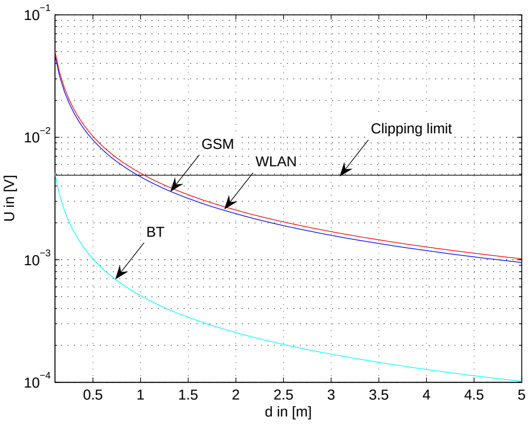

Fig. 3. Signal amplitudes of interferers considering free space attenuation

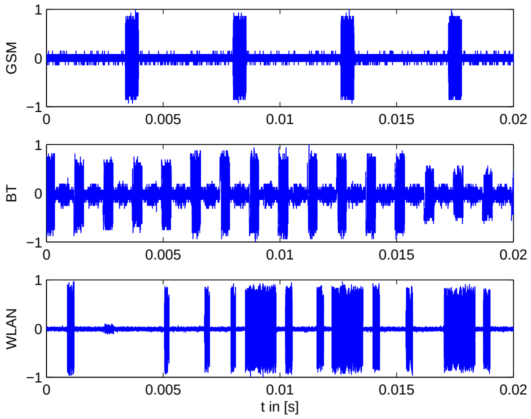

Fig. 4. Measured time domain signals of GSM, BT, and WLAN

3 bit range of the ADC. But if the input signal of the ADC exceeds the 6 bit due to an interference signal, the ADC suffers from clipping and no UWB signal can be resolved. Based on the assumptions above, the ADC is clipping for any noise or interference signal that is larger than seven times the desired signal amplitude.

In Fig. 3, signal amplitudes of BT, GSM and WLAN are shown for distances up to $d = 5$ meters. Each system is transmitting with its maximum allowed transmit power. Only free space attenuation is assumed for the interferers and a 5th order Butterworth high pass with $f_l = 3.1$GHz in the UWB receiver. For the expected 500MHz UWB receive signal power $P_{\mathrm{RX},500} = -50dBm$, which corresponds to a signal amplitude of 0.7mV @ 50 Ω, the clipping limit is 4.9mV. This clipping limit is exceeded by the interferers amplitudes only for distances below 1m. We again consider the extended BAN, i.e., only devices in the direct environment of a person are possible interferers. In such a close distance to a person, usually not more than one data and one speech connection plus maybe one headset are active. Therefore, we consider for the further interference investigations one GSM phone, one BT device and one WLAN device active at the same time.

IV. AVOIDANCE OF BURST INTERFERENCE

Considering different burst interferers, we distinguish two kinds of burst structures: periodic burst structures and non-periodic burst structures. In Fig. 4, normalized time domain signals of GSM, BT, and WLAN are depicted. As expected from standards, BT and GSM show a periodic burst structure while WLAN does not exhibit such a periodicity. Nevertheless, for all burst interferers segments between adjacent burst can be observed, where the channel is not occupied. Since UWB transmission is not possible if an interferer is active at the same time in the direct environment of a UWB receiver we propose UWB transmission in the time between adjacent interferer bursts. We refer to this approach as *temporal cognitive UWB medium access*.

In the following, we assume that the channel has two different states: occupied or unoccupied. If the channel is occupied, no UWB transmission is possible, i.e., UWB transmission is only possible if the channel is unoccupied. To determine the unoccupied times, we measure the interference with a real time sampling oscilloscope. Since the interfering signal shall not be reconstructed and since we are only interested in the duration and position of the interfering bursts, the sampling frequency was chosen as $1\text{MSample}/s$. With such an undersampling, measurements were performed over a time of 5s.

A. Achievable Pulse Rate and UWB Packet Length

In Fig. 5, one exemplary channel occupancy is shown. We assume that the UWB device has a sleep mode. After wake up the UWB device senses the channel and directly transmits its data if the channel is not occupied by any interferer. Then, the UWB device has to transmit its data in a given latency time p. Each UWB packet has a packet duration b. Within each UWB packet (diagonal lined in Fig. 5), a preamble of duration x is present, e.g., used for synchronization issues. The number of unoccupied time slots N in a given latency time is determined by the interferers burst structure and the latency time, e.g., $N = 2$ for the example in Fig. 5. The duration of the ith unoccupied time slot is given by k_i. Due to the transmission in the FCC peak power limit, the pulse repetition frequency is limited to $1\text{pulse}/\mu$s [11], i.e., the maximum achievable pulse rate without interference is 1 Mpulse/s.

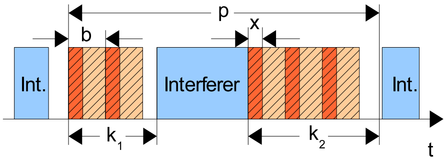

Fig. 5. Scheme to determine the maximum pulse rate with interfering bursts (solid) and UWB packets (lined)

Based on the assumptions above, the following expression for the pulse rate $r(b)$ can be achieved:

$$r(b) = \frac{b - x}{p} \cdot E\left\{\sum_{i=1}^{N} \left\lfloor \frac{k_i}{b} \right\rfloor\right\} \tag{5}$$

where $\lfloor \cdot \rfloor$ rounds the argument to the next smaller integer. The expectation $E\{\cdot\}$ is taken over different channel realizations. Division by p leads to a normalized pulse rate in Pulses/s. It can be seen that the packet length b has strong impact on $r(b)$. On one hand, the number of pulses per packet $b-x$ increases with b, on the other hand, the number of packets per empty slot time $\left\lfloor \frac{k_i}{b} \right\rfloor$ decreases with increasing packet length. This leads to the assumption that there exists an optimum packet length that yields the maximum pulse rate.

Since the expression in (5) is discontinuous, it is not possible to calculate the derivative to determine the optimum UWB packet length. Therefore, it is necessary to derive an approximation for the achievable pulse rate. $\lfloor \cdot \rfloor$ can be written as

$$\left\lfloor \frac{k_i}{b} \right\rfloor = \frac{k_i}{b} - c \tag{6}$$

with $c \in [0, 1)$. Setting $c = 0$, an upper bound for the pulse rate in (5) can derived as

$$r_{\text{max}}(b) = \frac{b-x}{p} \cdot E\left\{ \sum_{i=1}^{N} \left(\frac{k_i}{b} \right) \right\}. \tag{7}$$

This corresponds to having an integer number of UWB packets plus a fraction of one packet in an empty slot of duration k_i. Please note, that the preamble of this variable packet also scales with its packet length. The corresponding packet placement is shown exemplarily in Fig. 6 a).

Since $c \in [0, 1)$, a lower bound for the pulse rate in (5) can be achieved by setting $c = 1$.

$$r_{\text{min}}(b) = \frac{b-x}{p} \cdot E\left\{ \sum_{i=1}^{N} \left(\frac{k_i}{b} - 1 \right) \right\} \tag{8}$$

Corresponding to the example in Fig. 6 a), the packet placement for the lower bound is shown in Fig. 6 b). As well as for the upper bound, the preamble length of the variable packet scales here, too. Instead of considering the maximum and minimum value of c, we assume now a uniform distribution of c in $[0, 1)$, i.e., $E\{c\} = \frac{1}{2}$. Using this expectation value, it is possible to give an approximation for the achievable pulse rate in (5).

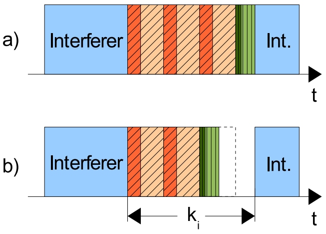

Fig. 6. UWB packet distribution in an unoccupied slot of duration k_i, a) using $r_{\text{max}}(b)$ from (7), and b) using $r_{\text{min}}(b)$ from (8); Interferer bursts are plotted solid, UWB packets are plotted diagonal lined, and fractional UWB packets are vertical lined

$$r_{\text{approx}}(b) = \frac{b-x}{p} \cdot E\left\{ \sum_{i=1}^{N} \left(\frac{k_i}{b} - \frac{1}{2} \right) \right\} \tag{9}$$

In Fig. 7, the pulse rates are shown for UWB if it is interfered by GSM, BT, and WLAN at the same time. It can be seen that the approximation $r_{\text{approx}}(b)$ fits $r(b)$ very well, especially in the range where the optimum packet length is located. The steps and the zigzag behavior of $r(b)$ are caused by the fact that by reducing the packet length slightly, one packet more can be transmitted in a given empty slot. As expected from the discussion above, $r(b)$ exhibits an optimum. If the UWB packet length is chosen to small, the pulse rate is low due to the high preamble overhead. With increasing UWB packet length the preamble overhead is decreased but the UWB packet may be longer then the unoccupied channel time k_i. For a latency time $p = 2\text{ms}$ and a preamble length $x = 100\mu\text{s}$, it can be observed that the pulse rate drops down to about 190 kPulses/s from 1 MPulses/s, which can be achieved without interference.

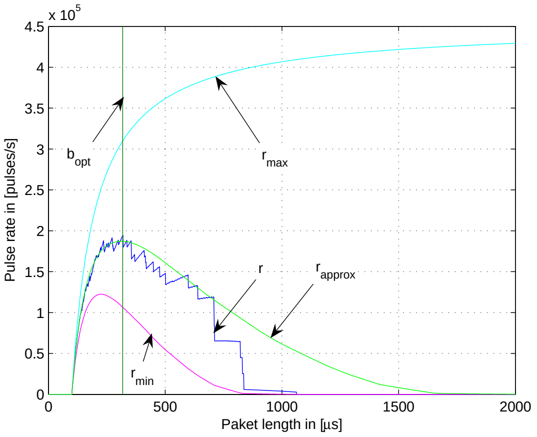

Fig. 7. Achievable UWB pulse rate when one GSM, one BT, and one IEEE 802.11b WLAN interferer are present at the same time, assuming $p = 2\text{ms}$ and $x = 100\mu s$

Due to the good approximation, we use $r_{\text{approx}}(b)$ to calculate the derivative and to determine the optimum UWB packet length. We find the optimum from (9) as:

$$\begin{aligned} \frac{dr_{\text{approx}}}{db} &= \frac{\bar{N}E\{k_i\}x}{p\,b^2} - \frac{\bar{N}}{2p} = 0 \\ \Rightarrow \frac{\bar{N}}{2p} &= \frac{\bar{N}E\{k_i\}x}{p\,b^2} \\ \Rightarrow b &= \pm\sqrt{2E\{k_i\}x} \end{aligned} \tag{10}$$

$\bar{N}$ denotes the mean value of N. In (10), only the positive solution for the UWB packet length makes sense. It can be seen that only the preamble length x and the expectation over the length of empty time slots k_i determine the optimum UWB packet length. The latency time p has only an impact on the optimum packet length if p is smaller than the usual empty time between two interfering bursts. Based on the above measurements and assumptions, an optimum packet length of $b_{opt} = 318\mu\text{s}$ is determined.

B. Packet Delays

The expression in (10) does not consider a possibly required maximum latency time. Although, the lengths of the empty time slots k_i are also determined by the latency time p it can happen that the latency time requirements are not met when transmitting UWB packets with the optimum packet length. Therefore, we investigate the packet delays, too. This investigation of the packet delays is also based on the same time domain measurements of GSM, BT, and WLAN. In Fig. 8, the time delay between the end of a successful transmitted UWB packet and the beginning of the next successful transmitted UWB packet is shown for different packet lengths. We consider 50%, 10% and 1% outage-delay as well as the maximum occurred delay, which corresponds to a 0% outage. For example, the 1% outage-delay means that 99% of all UWB packets are transmitted successfully with such a delay or less for a given packet length.

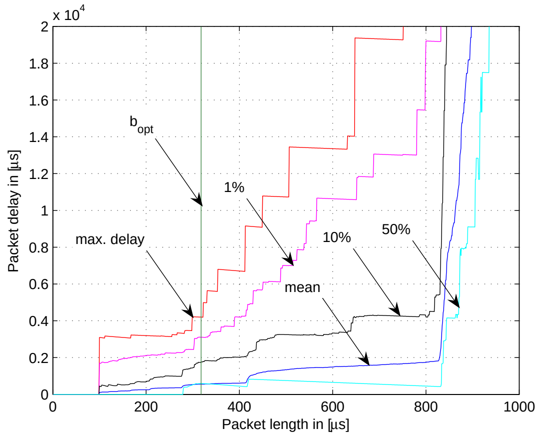

Fig. 8. Packet delays for different packet lengths

As expected, the delays increase with increasing packet length. For 50% and 10% outage, delays increase drastically for packets with a duration of more than 830μs. Delays for 1% outage and maximum delays remain almost constant up to a packet length of about 300μs. With increasing packet length both, maximum and 1% outage delays, grow and become several times larger than 10% outage delays or mean delays. For the above determined optimum packet length $r(b) = 318\mu$s, the 1% outage-delay is about 3.1ms. This means, that the proposed interference mitigation method can also be used for applications that require strict latency requirements. Moreover, it can be seen that for this scenario the maximum delay can only be marginally reduced using a packet length smaller than the optimum determined in (10).

In Fig. 9, the cumulative distribution function (CDF) over different delays is shown for the optimum UWB packet length determined by (10). It can be seen that about 42% of all packets are not delayed. 90% of all packets have a delay of less than 1.75ms and 99% of all packets have a delay of less than 3.1ms. The maximum present delay is 4.2ms. These delay values fit well with the delay values in Fig. 8. For comparison, CDF's are also plotted for packet lengths of 500, 700 and 900μs. As in Fig. 8 it can be seen that the delays increase with packet length and that much higher delays occur for packets with a length of more than 830μs.

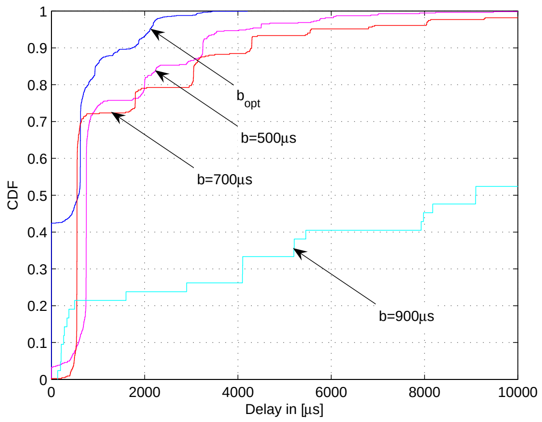

Fig. 9. Cumulative distribution function of the delays

V. CONCLUSIONS

Based on measurements of the background noise it was shown that such interference can be handled by using a high pass filter. To avoid burst interference, we proposed to use temporal cognitive UWB medium access. We presented an expression for the achievable UWB pulse rate in presence of burst interferers, and using an approximation of this expression, we showed that the optimum UWB packet length is only determined by the preamble length and the expectation of the empty slot durations. Achievable pulse rate and outage delays were investigated for a typical extended BAN scenario where one GSM phone, one BT, and one WLAN device were all active at the same time.

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