Detection of Modern Communication Signals Using Frequency Domain Morphological Filtering

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Abstract—**Safeguarding sensible areas and buildings from unauthorized use of wireless communication or drone intrusion requires a reliable and robust detection of modern communication signals. We present an algorithm for detecting UMTS, LTE and current drone communication signals in adverse environments. Morphological filtering in frequency domain is used to separate the desired signal from perturbations, thus allowing reliable detection. In a first step, the algorithm was validated on synthetic signals with narrowband single carrier perturbations and promising results were obtained. Long term field tests conducted in a prison in Germany revealed high performance in terms of low false alarm rates (0-0.8%) and high sensitivity (98.2-100%).**

Keywords—Morphological Filtering, LTE, UMTS, Signal Detection

I. - Introduction

Numerous application fields require a robust detection of modern communication signals [1]. An example can be found in prisons, where the unauthorized use of cellphones is prevented by detection and subsequent jamming or by detection, indoor-localization and subsequent confiscation of cellphones [2]. Another example is given by drones, which may constitute – when used with malicious intent – a threat for the security of sensible buildings and installations like nuclear power plants, airports and government buildings or to the privacy of prominent people [3]. The detection and subsequent jamming of these communication signals constitutes a potential solution to prevent such threats, and avoid disastrous consequences or unauthorized intrusion [3, 4]. However, robust and reliable detection of a specific signal in an adverse environment is not an obvious task. To avoid false alarms related to perturbations and noise, characteristics and peculiarities of the useful signal are often used to enhance the signal [1, 5], thereby reducing the influence of harmful noise or perturbations. The method used to enhance the quality of the signal depends mainly on the nature of signal and noise [6]. Modern communication signals often have large bandwidths, specific spectral shapes and do yield cyclo-stationary behavior [7]. Perturbing signals may be non-stationary, and, compared to the useful signal, may have extremely high power, such as for example single carrier perturbations. Such characteristics prevent the application of classical signal enhancement algorithms like Wiener Filtering, spectral subtraction and/or subspace approaches. Herein we propose to exploit the characteristic morphological shape of the short term power spectral density (PSD) of modern communication signals by performing signal enhancement prior to detection by morphological filtering [8]. The PSD of the recorded signal undergoes a morphological filtering with a specific structural element (SE), which allows the separation of the useful signal from the perturbation, and renders the detection more reliable and robust. The use of morphological filtering is motivated by its high performance in numerous applications where characteristic signal shapes are given [9, 6, 10]. We show that the proposed method yields high performance in detecting cellphones of the third and fourth generation and of modern drones, i.e. the Phantom 3.

II. Signals And Method

A. Background

Over the last decades technology for mobile radio communication has considerably evolved leading to communication standards of the third generation, namely the Universal Mobile Telecommunication System (UMTS) [11], and the fourth generation, the Long Term Evolution (LTE) [12]. In comparison to the older standards, UMTS and LTE have an enhanced data transfer rate, mainly achieved by improved spectral efficiency and advanced multiple access methods. UMTS applies Code Division Multiple Access (CDMA), whereby the information bearing digital signal is spread through multiplication with a spreading code [11] on a bandwidth of approximately 4MHz with a characteristic spectral shape. Methods and algorithms for detecting UMTS signal proposed in literature are mainly based on non-parametric or parametric estimation of the PSD [13]. LTE uses the spectral bandwidth in a different manner, modulating the information bearing digital signal on large number of narrowly spaced neighboring orthogonal subcarriers [12]. This results in characteristic shaped PSDs with cyclo-stationary behavior. This modulation scheme is called Orthogonal Frequency Division Multiplex (OFDM) and associated detection methods proposed in literature exploit these cyclo-stationary properties in PSD or correlation based approaches [14].

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Modern commercial drones often base their wireless communication on standard protocols. As an example, we considered here the Phantom 3 from DJI, a bestseller drone for hobbyists and one of the market leaders in drone business. This drone uses two different RF communications: the remote control and the video/telemetry data streaming. Both are located in the Industrial, Scientific and Medical Band (ISM-Band). The video/telemetry data streaming from the drone to the remote control splits the ISM-Band into ten dedicated channels of 10MHz bandwidth and applies OFDM on each channel. The second communication from the remote control to the drone applies Frequency Hopping Spread Spectrum (FHSS) in the entire ISM-Band with a bandwidth of 2MHz.

B. Method

In the previous paragraph, modern communication signals such as UMTS, LTE and drone signals and their specific spectral characteristics have been presented. Each of these signals has characteristic spectral shapes, which we exploited here in a signal specific enhancement algorithm (see Figure 1). In a first step, a statistically robust estimation of the short term Power Spectral Density (PSD) was processed using Welch's spectral estimator [1]. At instant n the PSD $\hat{P}_{xx,n}(f)$ was obtained as the average of M periodograms, computed by the FFT on the last M Hanning-windowed signal segments of length L with an overlap of $L/2$. The parameters of this spectral operator M and L have been chosen optimally with respect of the time frequency characteristics of the communication signals under investigation (see TABLE I).

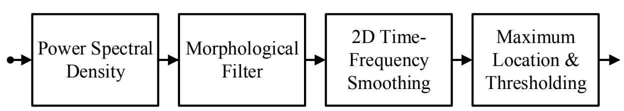

Figure 1. Block diagram of proposed detection algorithm

In a second step, signal enhancement was performed using morphological filtering. This is motivated by the fact that a large number of false alarms were obtained in preliminary field tests using only threshold guided maxima location on PSD. This was due to single carrier perturbations. The proposed algorithm is based on the assumption that the spectral shape of the communication signal of interest and the perturbation signals are sufficiently different for morphological filters to operate with discriminating power. Morphological filters are non-linear operators which assign an output value to an ensemble of input values. The assignment is performed with minimum or maximum operators between the structural element and the ensemble of input values [8]. In order to provide maximal noise reduction the structural element should be chosen to match the characteristic spectral shape of the useful signal [9]. The two basic morphological operators were dilation (1) and erosion (2), defined as follows:

$$(x \oplus f)(n) = \max_{m=0,\dots,F-1} \{x(n-m) + f(m)\} \tag{1}$$

$$(x \ominus f)(n) = \min_{m=0,\dots,F-1} \{x(n+m) - f(m)\} \tag{2}$$

where $x(n)$ is the signal to be processed, $f(n)$ the structural element and F the length of the structural element. We approximated the characteristic PSD shape of the communication signals in the logarithmic domain by a rectangular window, which subsequently was used as the structural element. The interesting properties of the morphological operators emerge when used in conjunction: erosion followed by dilation which yields the opening operator

$$(x \circ f)(n) = (x \ominus f \oplus f)(n)\,. \tag{3}$$

The opening operator is ideally suited to perform noise reduction in presence of single carrier perturbations. Indeed, an opening with a structural element which is slightly narrower than the signal of interest erases narrowband perturbations. This property is illustrated in Figure 2. where the PSD of an UMTS signal with narrowband perturbations is shown.

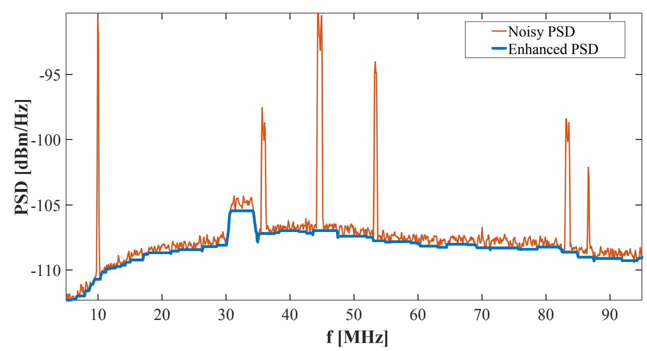

Figure 2. PSD of UMTS signal before and after morphological filtering

It can be observed that the perturbations in the noisy signal are successfully suppressed by morphological filtering. The enhanced signal contains mainly the noise floor and the UMTS signal of interest at approximately 32.5MHz.

Perturbations larger than the signal of interest may also be filtered through morphological processing. This can be achieved by additionally using an opening operator with a structural element larger than the bandwidth of the signal of interest. The combined operation corresponds to the subtracting scheme [10] as shown in Figure 3.

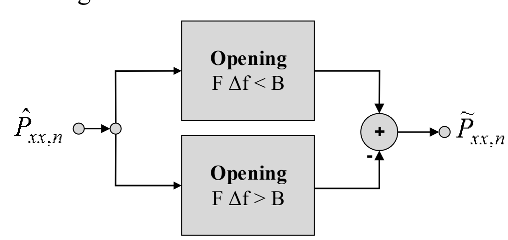

Figure 3. Signal extraction using morphological filter. F is the length of the structural element, Δf is the spectral resolution and B is the bandwidth of the useful signal.

An illustration of algorithm performance on drone signals is shown in Figure 4 as a time frequency plot. The drone signal of interest consisting of narrowband remote control signal (2MHz) and large band video streaming signals (10MHz) is shown in Figure 4.a.). Processing the PSD with the morphological filtering scheme of Figure 3 using appropriate length of the structural elements separate the remote control signal (Figure 4.b.)) and the video streaming signal (Figure 4.c.)). Prior to detection by a threshold guided maximum location, the variance of the discriminating PSD was further reduced by time-frequency smoothing operation, consisting in an averaging of PSDs over time and smoothing over frequency.

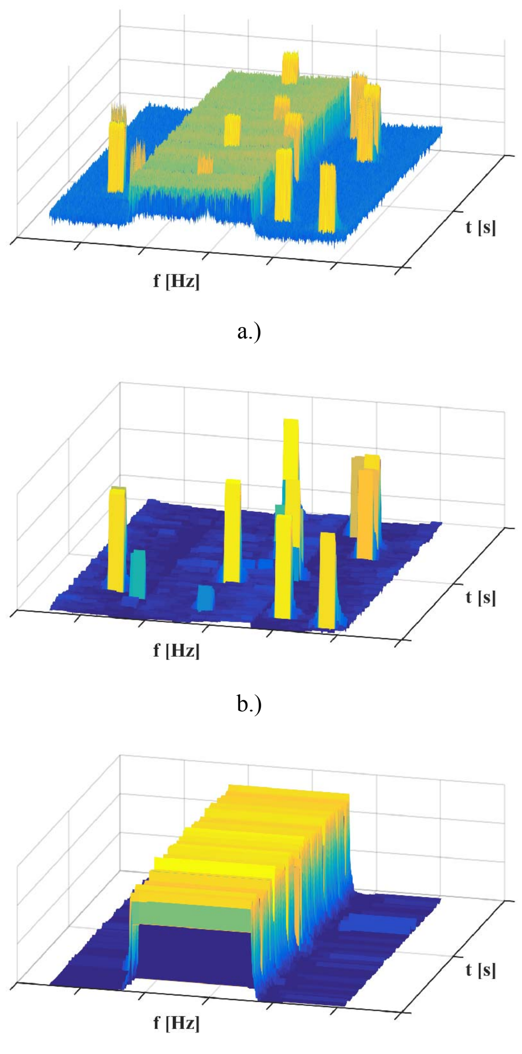

Figure 4. a.) Recorded signals consisting of remote control and video streaming data b.) Extracted remote control signal c.) Extracted video stream signal

C. *Implementation and Data Acquisition*

The proposed algorithm was implemented on two different Software Defined Radio (SDR) platforms. For the application to UMTS and LTE detection it was implemented as part of a Modular Jamming System, a professional high quality product of the innovative Swiss Company COMLAB [2]. For the drone detection application it was implemented on the USRP X310 from Ettus Research [15]. Both SDR platforms have two wideband Rx/Tx channels, a high-speed Ethernet interface to a host and a Field Programmable Gate Array (FPGA) for the implementation of user defined digital signal preprocessing (see Figure 5). The goal of the preprocessing in the FPGA is to reduce the data streaming rate, such that a host located software environment like MATLAB, LabVIEW or GNU Radio can handle the data stream, post-process and record it in real time. In the algorithm depicted in Figure 1, high data rate is necessary for the short term PSD processing since signal activities must be monitored in our application in a bandwidth of approximately 100MHz. This short term PSD has to be reprocessed at a rate of about half a millisecond to gather the burst-like signal activity, which implies that this first processing step renders a large reduction in terms of the associated data transfer rate. Accordingly we implemented the short term PSD on the FPGA while performing the remaining operations and signal recording in Simulink/MATLAB.

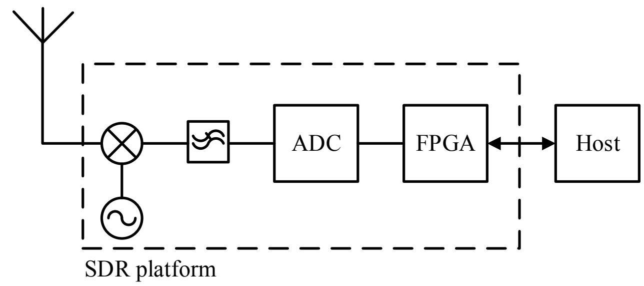

Figure 5. Block scheme of SDR platform and host connectivity used for the algorithm implementation

III. Validation

A. *Parametrization of Algorithm*

The proposed algorithm has a parametric structure and only an optimal choice of its parameters provides reliable performance for a given application. The main parameters are the FPGA sampling frequency, the FFT order L, the number of spectral averages M of the PSD and the length F of the morphological filter. The optimal values of these parameters are related to the time-frequency characteristics of the given communication signals but limited by FPGA hardware constraints. Some main guidelines can be summarized as follows: 1) the sampling frequency should allow the observation of the whole bandwidth of the communication standard; 2) the order L of the FFT should allow sufficient frequency resolution, such that spectral shapes of the useful signal may by represented in reliable manner; 3) The number of spectral averages M should be chosen as large as possible to minimize the variance of the spectral estimator while allowing convergence over time on the typical burst-like structure of a given communication signal; 4) The length of the morphological signal should be chosen considering the bandwidths of useful signal and perturbations.

The communication standard UMTS applies CDMA [11] and spreads the signal over approximately 4MHz. To comply with the requirements of the Modular Jamming System of COMLAB [2], a temporal resolution of 330µs was required. By setting the FFT order L to 2048 and the number of spectral averages M to 32 a spectral resolution of approximately 100kHz and a temporal resolution of 330µs results. To reach a bandwidth of almost 4MHz the length F of the morphological filter is set to 36. The LTE standard specifies a subcarrier spacing of 15kHz and time allocation in sub-frames of 1ms. According to the E-UTRA standard [12], the uplink band of interest ranges over a bandwidth of 70MHz. To achieve a spectral resolution close to the subcarrier spacing with a reasonable FFT order L, the observed bandwidth has been split into two sub bands of 36MHz each. With an FFT order L of 2048 and a spectral averaging over M = 17 past periodograms, we achieve a spectral resolution of about 17kHz and a time resolution of 1ms. The length of the structural element is set to 11, since the smallest allocated bandwidth in E-UTRA is 180kHz. In drone applications the up- and downlink must be detectable due to the usage of the same ISM-Band. The considered Phantom 3 from DJI use FHSS of approximately 1ms length, with 2MHz bandwidth for the remote control and an OFDM modulated continuous video stream of 10MHz bandwidth. The chosen FFT order L of 1024 results in a spectral resolution of 195kHz. The number of averaged periodograms M is set to 32 which results in a temporal resolution of 160µs. To detect both signals separately, two morphological filter are used with a length F of 56 for the video stream and 10 for the remote control signal. The adaption to other drone types is simply realized by identifying their communication standard and change the parameters L, M and F according to their signal characteristics.

TABLE I. summarizes the optimal parameters determined during the development phase.

TABLE I. ALGORITHM PARAMETERS

Application	Parameter				
	Sampling frequency [MHz]	***Observed Bandwidth [MHz]***	***L***	***M***	***F***
UMTS	200	100	2048	32	36
LTE	216.25	2x 36	2048	17	11
Phantom 3	200	120	1024	32	56 / 10

B. Protocols and Signals

In order to validate the algorithm a large number of signals have been recorded for each of the three applications. The protocol has been designed in such a way as to mimic real world conditions of modern communication standards in restricted areas. Such areas are typically located in either secluded locations or densely populated areas, like cities. For both cases, we observed mainly single carrier or narrow band perturbations. In densely populated areas, communication signals from the neighborhood surrounding the restricted area constitute perturbations which may lead to false alarms. In this case, directional antennas with a suitable front-to-back ratio can be used to attenuate these perturbations. The following list gives an overview of the generated and recorded datasets for the validation of the detection algorithm.

- UMTS signals with frequencies ranging from 1922.5MHz to 1972.5MHz and levels from -120dBm to -70dBm were generated with the vector signal generator SMIQ 03B of Rhode & Schwarz. Narrowband single carrier perturbations (bandwidth 2kHz) with levels at -70dBm were added and 2.5 Mio stochastic realizations of this process were conducted.
- LTE signals consisting of 1ms active and 9ms inactive segments and levels ranging from -120dBm to -70dBm were generated with the vector signal generator SMU200A from Rhode & Schwarz. Narrowband single carrier perturbations (bandwidth 2kHz) with levels at -70dBm were added and 2.5 Mio stochastic realizations of this process were conducted.
- Drone signals were directly recorded from the Phantom 3 during a period of 96 seconds (48 recordings of 2s) with a distance from the drone to receiver of 5m. To simulate harsh noisy environments, Gaussian white noise was added with a signal-to-noise ratio varying from 15dB to 0dB in 0.1 Mio stochastic realizations of a Monte Carlo simulation.

C. Results

In the considered applications of cellphone and drone detection the performance criteria of interest are the True Positive Rate (TPR) and the corresponding False Positive Rate (FPR) at a given level of the input signal. TPR is the percentage of correct detections, called the sensitivity, and FPR is the percentage of incorrect detections, called false alarm rate. TABLE II. shows the resulting performance.

TABLE II. PERFORMANCE RESULTS

Application	Performance		
	Sensitivity (TPR)	***False Alarm Rate (FPR)***	***Input Level of wanted Signal***
UMTS	100%	0%	≥ -105dBm
	98.2%	0%	-110dBm
LTE	100%	0%	≥ -110dBm
	98.9%	0.3%	-117dBm
Drone	100%	0.4%	≥ -100dBm
	99.3%	0.8%	-110dBm

Detection performance reveals an extraordinary robustness of the proposed algorithm in terms of rejecting strong narrowband perturbations. All considered signals could be reliably detected, with high sensitivity and low false alarm rate. A closer inspection of the results points out that TPR values for the UMTS and drone application are almost identical. We explain this by similar detection time constraints. For the LTE application longer detection time constraints were allowed leading to better detection performance.

D. Field Tests

In a first phase, the robustness of the proposed algorithms were evaluated in a field environment with large number of strong narrow-band perturbation signals (RF-development laboratory). The algorithms were tested over a duration of three days. No false alarms have been registered while providing a sensitivity setting of 98.2%, 98.9% and 99.3% for UMTS, LTE and the Phantom 3, respectively. The drone detection implementation was also evaluated in line of sight conditions in a sparsely populated urban area yielding drone detection alarms at distances up to 2km.

In a second phase, the presented UMTS and LTE cellphone detection implementation was installed permanently in a prison (Berlin, Germany) triggering a professional high quality Modular Jamming System [2]. This system prevents unauthorized use of cellphones to the entire satisfaction of the operating-staff since its installation in 2014.

E. Discussion and Limitations

The presented generic algorithm for the detection of modern communication signals was initially developed without morphologic filters. Pilot field tests revealed high number of false alarms due to narrowband perturbations, requiring a further development using additional signal processing by morphological filtering. The increased robustness rendered the detection algorithm able to comply with the high quality requirements of modern security applications.

The signal enhancement of the proposed algorithm based on morphological filtering with a rectangular structural element exploits differences in spectral bandwidth of useful and perturbation signals. Thus, perturbation signals with similar bandwidth as the useful signals may lead to false alarms. We have observed this case in the drone detection application, where Bluetooth and WLAN communication signals were potential sources to trigger false alarms during indoor tests. However, the drone detection application was conceived for outdoor operation, where the low-range Bluetooth and WLAN signals are often sufficiently attenuated to induce false detections. If needed, RF scene analysis [16], which takes the known positions of WLAN access points into account, could be applied to minimize the false alarm rate.

IV. CONCLUSIONS

The proposed algorithm, which combines the short term PSD and morphological filters, provides a reliable method to separate strong interferences from the desired signal and detects modern communication signals with high sensitivity (98.2-100%) and low false alarm rates (0-0,8%).

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