Receiver Architecture for Cognitive Positioning with CDMA and OFDM signals

Pedro Figueiredo e Silva*, Gonzalo Seco-Granados** and Elena Simona-Lohan*
* Department of Electronics and Communications Engineering, Tampere University of Technology, Finland
{pedro.silva,elena-simona.lohan}@tut.fi
** Signal Processing for Communications and Navigation (SPCOMNAV), Universitat Autònoma de Barcelona, Spain
gonzalo.seco@uab.es

***Abstract*—This paper proposes a cognitive positioning architecture. This architecture uses cyclostationary analysis to understand the contents of the spectrum surrounding the receiver and exploit this information for activating the necessary tracking and demodulation loops. This paper assumes the presence of CDMA and OFDM signals. The results show the performance of the spectrum sensing technique used along with the expected positioning accuracy.**

***Index Terms*—Cognitive positioning architecture, spectrum sensing, signals of opportunity, approximate maximum likelihood.**

A cognitive radio (CR) is a device aware of its environment, allowing the coexistence with other radios that might lack cognition features [1]. The coexistence is guaranteed by monitoring the spectrum for unused frequency subbands [2], [3]. In some cases, the CR may need to know its location. However, while a position fix is easy to obtain in an outdoor environment, indoor environments are particularly difficult for current positioning technologies, such as global navigation satellite systems (GNSS). Consequently, there is a need for better indoor navigation, at a reasonable price. In indoor environments cellular and Wi-Fi signals are already widely deployed, their use for indoor positioning systems is an alternative to other dedicated systems. The main purpose of Wifi and celular signals is to provide data and voice communication links, therefore they are known as signals of opportunity (SoO) when used in a navigation context.

Enabling navigation through SoO, requires a device capable of simultaneously acquiring, tracking and decoding a multitude of signals, raising difficulties at the implementation level. Besides the physical limitations of current devices, the power consumption is another concern, and it does not benefit from adding extra sensors. Since cognitive radios and advanced signal processing techniques are becoming the norm for future telecommunication standards [4], it should be possible for positioning systems to tap into this cognition layer. With such information, these systems could manage the existing hardware and provide more efficient hybridisation of different sensor data [5], [6].

The architecture proposed in this paper, aims to speed up the acquisition, tracking and demodulation of the incoming signals in comparison to the traditional approach illustrated in Fig. 1.A. To fulfil that objective, the signals at the input of the front end are merged in a single digital representation and fed to the spectrum sensing block Fig. 1.B. These signals can be, for example, Wi-Fi, Bluetooth, RFID, LTE, as well as other signals and the goal of the block is to identify which signals are present in the spectrum at a given time. This information is carried over to the cognitive positioning engine, which is responsible for performing the signal selection for the acquisition and tracking stages. The reason of performing such signal selection is either to increase the performance requirements or improve the power and resource usage of the device. Later on, this is exemplified with an example where different number of orthogonal frequency-division multiplexing (OFDM) and code division multiple access (CDMA) emitters are used to determine the location of a mobile receiver.

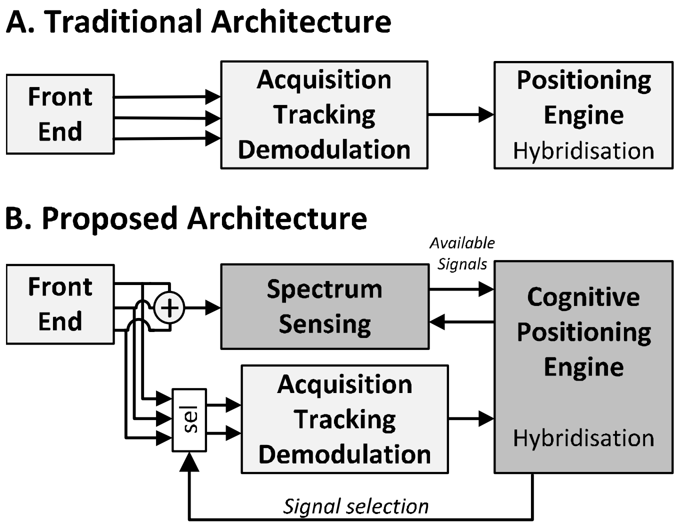

Fig. 1. Example of a possible cognitive positioning system.

I. Proposed architecture

The following discussion focuses on signal detection and signals using their cyclostationary features, at the cognitive positioning engine. CDMA and OFDM signals are considered due to their popularity in current and future communication systems. Besides that, the authors of [7], [8] have found them suitable for positioning based on timing and received signal strength (RSS) estimates [9], [10].

A. Signal model

CDMA and OFDM signals are assumed to be present in the surrounding spectrum of a receiver, such as the one depicted in Fig. 1.B, and at the spectrum sensing block input, their representation is given by $z(t)$,

$$z(t) = d(t) + m(t) + n(t), \tag{1}$$

where $d(t)$ is a CDMA signal, $m(t)$ a OFDM signal and $n(t)$ is white Gaussian noise (WGN) of double-sided power spectral density equal to $\frac{N_0}{2}$. If either one of the signals is absent during a period of time, their representation is set to zero. For clarity, the channel is assumed to have flat frequency response, but the ideas can be extended to frequency-selective channels as well.

The CDMA signal, $d(t)$, is given by,

$$d(t) = \begin{cases} E_c \sum\limits_{n=-\infty}^{+\infty} \sum\limits_{k=1}^{\mathrm{SF}} c_k(n) p(t - kT_c - nJT_c) \\ 0, \text{ when signal absent.} \end{cases} \tag{2}$$

where E_c is the chip energy, SF is the spreading factor, $c_k(n)$ is the chip value (+1 or -1) for k^{th} chip during n^{th} symbol, $p(t)$, a pulse shaping function, T_c the chip interval.

As for the OFDM signal, $m(t)$, is described by,

$$m(t) = \begin{cases} A \sum\limits_{n} \sum\limits_{k=0}^{N-1} X_n(k) e^{j2\pi k \Delta_f t} q(t - nT_U) \\ 0, \text{ when signal absent,} \end{cases} \tag{3}$$

where $A = \sqrt{(NT_U E_m)}$ is a multiplicative constant normalising the OFDM symbol energy, N is the number of subcarriers, E_m is the average energy of M-QAM data symbols which forms the OFDM symbols, $X_n(k)$ is n-th OFDM symbol expressed as a vector consisting of l data symbols, and $q(t)$, a pulse shaping function. T_U is the symbol period before being extended with the cyclic prefix. With the introductuion of the cyclic prefix, the total symbol period, T_{symbol}, is defined as

$$T_{\text{symbol}} = T_{GI} + T_U, \tag{4}$$

where T_{GI} is the duration of the guard interval, which is occupied by the cyclic prefix, plus the duration of the useful symbols, $T_U = \Delta_f^{-1}$, which is chosen to guarantee orthogonality of the OFDM subcarriers for their given frequency spacing Δ_f. In the frequency domain, the signal occupies frequencies in the range $[-B, B]$ MHz.

B. Cyclostationary features

A signal $z(t)$ is wide-sense cyclostationary if its time varying autocorrelation function $R(t, \tau)$ is periodic in time, t, for each lag parameter, τ. Hence, it can be represented as a Fourier series,

$$R(t, \tau) = E\{z(t) z^*(t + \tau)\} = \sum_{\gamma} R^{\gamma}(\tau) e^{j2\pi\gamma t}, \tag{5}$$

where the sum is taken over multiples of fundamental cyclic frequency γ for which the cyclic autocorrelation function is defined as,

$$R^{\gamma}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} R(t, \tau) e^{-j2\pi\gamma t} dt. \tag{6}$$

The spectral correlation function (SCF) [11], $S^{\gamma}(f)$, is the Fourier transform of R^{γ} given as,

$$S^{\gamma}(f) = \int_{\mathbb{R}} R^{\gamma}(\tau) e^{-j2\pi f\tau} d\tau. \tag{7}$$

Periodicities in the signal, such as those produced by the symbols or the repetitions of the spreading sequence are responsible for the appearance of spectral lines in the SCF domain. The locations of the spectral lines are referred to as cyclic frequencies. When the signal is purely random, as it is the case with AWGN, the value of the SCF is zero for every cyclic frequency, except at $\gamma = 0$. An example of SCF for a mixture of CDMA and OFDM signals with noise is shown in Fig. 2, where α_m and β_m are the cyclic frequencies for each signal type, respectively, which are defined in the following paragraphs.

In the context of this study, the cyclic frequencies of interest are those specific to CDMA and OFDM signals. For the CDMA signal the SCF can be expressed [6], [12] as

$$S^{\gamma}(f) \cong D(f - \frac{\gamma}{2}) D^*(f + \frac{\gamma}{2}) \sum_{k=-\infty}^{\infty} \delta_{\left(\gamma - \frac{k}{T_{\text{symbol}}}\right) T_c \, mod \, 1} + \frac{N_0}{E_c \mathrm{SF}} \delta_{\gamma}, \tag{8}$$

where $D(f)$ is the Fourier transform of $d(t)$, $\delta_{(\gamma - \frac{k}{T_{\text{symbol}}} T_c) \bmod 1}$ the Kronecker delta function having value 1 when $(\gamma - \frac{k}{T_{\text{symbol}}} T_c) \, mod \, 1 = p, p \in \mathbb{Z}$ and zero otherwise, T_c is the chip interval length, T_{symbol} the symbol period. Its theoretical cyclic frequencies [12] are dependent on both the chip rate, f_c, and SF and are contained in $\mathcal{A}$,

$$\mathcal{A} = \{\alpha_0, \alpha_1, \cdots, \alpha_m\}, m \in \mathbb{Z}, \tag{9}$$

$$\forall \alpha_m : \alpha_m \in \left\{ kf_c \, , \, kf_c \pm n \frac{f_c}{SF} \right\} \wedge k, n \in \mathbb{Z}. \tag{10}$$

The OFDM SCF [13] is estimated by,

$$S^{\gamma}(f) = \frac{\delta_r^2}{T} \sum_{n=0}^{N-1} Q\left(f - \frac{n}{T_{\text{symbol}}} + \frac{\gamma}{2}\right) Q^*\left(f - \frac{n}{T_{\text{symbol}}} - \frac{\gamma}{2}\right), \tag{11}$$

which is non-zero for every $\gamma = \frac{k}{T_{\text{symbol}}}$ and zero otherwise and $Q(f)$ is the Fourier transform of the pulse shape function. The OFDM theoretical cyclic frequencies are found to be in $\mathcal{B}$,

$$\mathcal{B} = \{\beta_0, \beta_1, \cdots, \beta_n\}, n \in \mathbb{Z}, \tag{12}$$

$$\forall \beta_n : \beta_n \in \left\{ k \frac{1}{T_{\text{symbol}}} \right\} \wedge k \in \mathbb{Z}, \tag{13}$$

where each β_n location is related to the symbol period [14].

The proposed detector requires the knowledge of both $\mathcal{A}$ and $\mathcal{B}$. For that reason, parameters for both signals need to be known by the algorithm. Regarding the CDMA signal, the

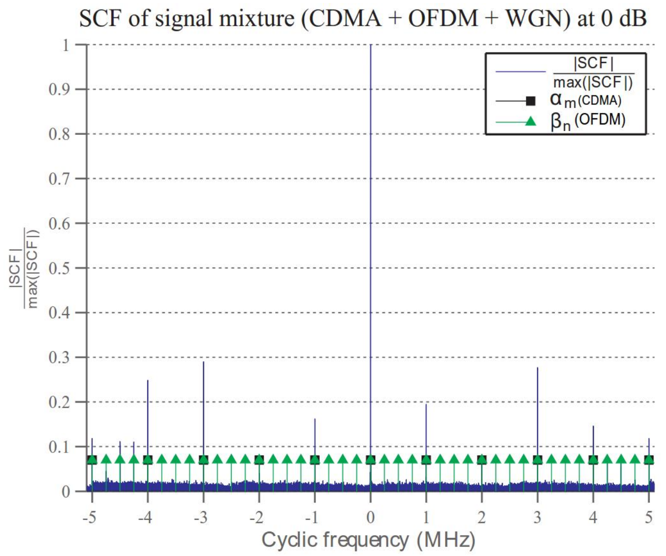

Fig. 2. Section of the SCF at frequency zero $S^{\alpha}(0)$.

chip rate and spreading factor are necessary. As for OFDM signal, the total number of carriers and bandwidth.

C. Feature detector

The proposed feature detector, inspired in [15] and [16], determines if certain cyclic frequencies are present or not in the SCF. The algorithm starts by defining several windows, **W**, over the absolute value of the SCF. These windows are placed over the SCF at specific cyclic frequencies, γ,

$$\boldsymbol{W} = [\gamma_i - \epsilon, \gamma_i + \epsilon] \tag{14}$$

and with ϵ set to a value that guarantees, γ_i is the only cyclic frequency present (Table I). This is the input to the algorithm (Fig. 3). Afterwards, the algorithm computes the standard deviation, σ, and mean, μ, within each window. The ratio between the standard deviation and the mean result in an activity indicator, I,

$$I = \frac{\sigma}{\mu}, \tag{15}$$

which is compared to a threshold, V_{th}, to decide whether a cyclic frequency is present or not. When no cyclic frequency is present the values over $\boldsymbol{W}$ remain close to zero, as per definition of the SCF. Therefore, from (15) is understandable that for in case of a cyclic frequency, the standard deviation will significantly increase the value of I, since the mean will be less sensitive to this outlier. When cyclic frequencies are absent in $\boldsymbol{W}$, the value of I is consistent throughout the windows and relates the mean and variance of the χ^2 distribution of $\boldsymbol{W}$. $\boldsymbol{W}$ is χ^2 distributed, due to the absolute square (magnitude) operation. For a more robust approach, a goodness of fit to the χ^2 distribution should be done [17]. When the test fails, no cyclic frequency should be present in $\boldsymbol{W}$.

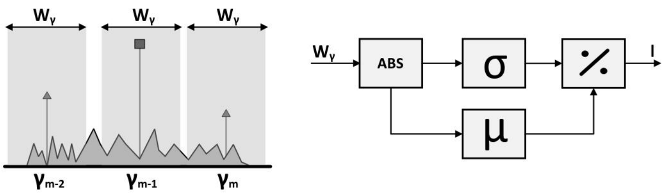

Fig. 3. Algorithm's window (left) and detector's diagram block (right).

D. Decision process

The detection mechanism is used to test the presence of certain cyclic frequencies in sets $\mathcal{A}$ and $\mathcal{B}$. This information is used by a K out of M detector [18] to point out whether a CDMA or an OFDM signal is present or not. Since some of the cyclic frequencies might overlap, as it is the case in this work, the detection is performed over two stages. Therefore, the decision about whether a signal is present or not is taken following the flow chart in Fig. 4, where the following definitions have been used:

$$\mathcal{H}_{1.1} = \begin{cases} \text{CDMA and OFDM with AWGN} \\ z(t) = x(t) + y(t) + n(t), \end{cases} \tag{16}$$

$$\mathcal{H}_{1.2} = \begin{cases} \text{CDMA with AWGN,} \\ z(t) = x(t) + n(t), \end{cases} \tag{17}$$

$$\mathcal{H}_{1.3} = \begin{cases} \text{OFDM with AWGN,} \\ z(t) = y(t) + n(t), \end{cases} \tag{18}$$

$$\mathcal{H}_{0} = \begin{cases} \text{AWGN only,} \\ z(t) = n(t), \end{cases} \tag{19}$$

the decision of whether a signal is present and the sub-sequent positioning options is done by the process in Fig. 4.

In more detail, a CDMA signal is present if no OFDM cyclic frequencies are detected in the set $\mathcal{B} - (\mathcal{B} \cap \mathcal{A})$. If cyclic frequencies are observed in such a set it means that an OFDM signal is also present in the mixture. However, both signals are only present if K cyclic frequencies from both $\mathcal{B}$ and $\mathcal{A}$ are detected.

In this approach, it is not possible to look only at the exclusive set of CDMA cyclic frequencies, since the set $\mathcal{A} - (\mathcal{B} \cap \mathcal{A})$ is an empty set.

E. Hybridisation algorithm

Time of arrival (TOA) positioning methods became quite popular in the navigation field due to several systems, such as the global positioning service (GPS), however their main disavantage is the requirement of a synchronised network. For example, for GNSS the satellites are synchronised through the ground control stations and the receiver clock offset is estimated along with the position estimates. In mobile telecommunications systems, the synchronisation is provided by the control at the base stations.

In this paper, an approximate maximum likelihood (AML) approach is used to solve a 2D position estimate of a receiver [19]. Lack of synchronisation is assumed among CDMA and

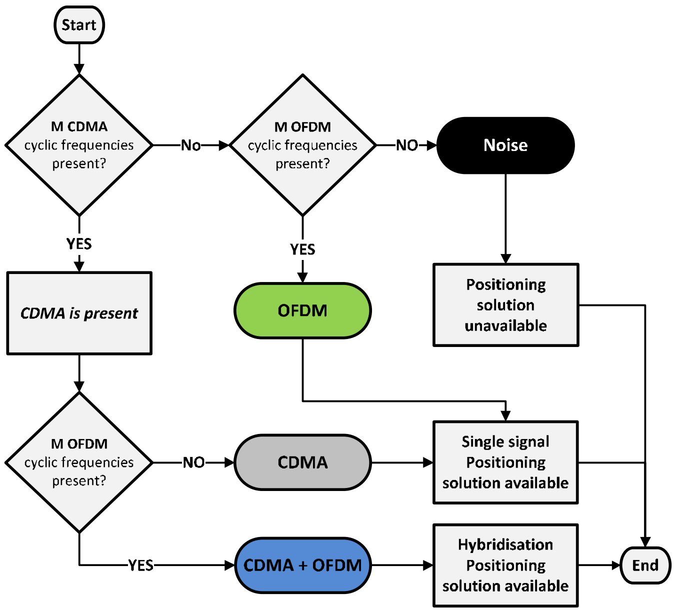

Fig. 4. Cognitive positioning algorithm with SCF-based detection.

OFDM emitters, but each emitter of the same technology is assumed to be synchronised. In addition, CDMA and OFDM measurements are considered to have different levels of quality, with OFDM leading to more noise time-delay estimates.

Assuming the presence of N_E emitters, E, the distance, r_i, between them and the receiver is given by,

$$r_i = \sqrt{x - x_i)^2 + (y - y_i)^2},\ i = 1, 2, ..., N_E. \tag{20}$$

The measured distances are given by,

$$l_i = r_i + \varepsilon_i, i = 1, 2, ..., N_E \tag{21}$$

where, ε, represents the timing errors associated with the underlying signal used to compute the pseudoranges l_i. Therefore, the magnitude of ε is set from a normal distribution with zero mean mean and variances σ_{CDMA} and σ_{OFDM}, depending on whether a CDMA or an OFDM signal is used. TOA estimators with CDMA offer better performance than TOA estimators with OFDM, thus the assumption of $\sigma_{OFDM} > \sigma_{CDMA}$ [20]. Nevertheless, this is not a requirement for the algorithm to work. The essential is that different signals will have different noise variances.

A TOA vector, $\boldsymbol{T}$, can be obtained by diving (21) by the speed of the medium, v, resulting in,

$$\boldsymbol{T} = \frac{\boldsymbol{r}}{v} + \frac{\boldsymbol{\varepsilon}}{v} = \boldsymbol{T}^0 + \boldsymbol{\varepsilon}, \tag{22}$$

where,

$$\boldsymbol{r} = [r_1, ..., r_{N_E}]^T = \boldsymbol{r}(\boldsymbol{\Theta}),\ \boldsymbol{\Theta} = [x, y], \tag{23}$$

and

$$\boldsymbol{\varepsilon} = [\varepsilon_1, ..., \varepsilon_{N_E}]^T. \tag{24}$$

The conditional probability density function of $\boldsymbol{T}$ given $\boldsymbol{\Theta}$ is given by,

$$f(\boldsymbol{T}|\boldsymbol{\Theta}) = (2\pi)^{-\frac{N_E}{2}} (\det \boldsymbol{Q})^{-1/2} \exp\left\{-\frac{J}{2}\right\}, \tag{25}$$

where,

$$J = \left[\boldsymbol{T} - \frac{\boldsymbol{r}(\boldsymbol{\Theta})}{v}\right]^T \boldsymbol{Q}^{-1} \left[\boldsymbol{T} - \frac{\boldsymbol{r}(\boldsymbol{\Theta})}{v}\right], \tag{26}$$

and

$$\boldsymbol{Q} = \mathbb{E}[\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}^T] = \text{diag}[\sigma_1 \cdots \sigma_{N_E}]. \tag{27}$$

The maximum likelihood estimate of the receiver position is the Θ that minimises J [19], which can be obtained as follows,

$$\boldsymbol{A\Theta} = \boldsymbol{b} \Leftrightarrow$$
$$\Leftrightarrow 2\begin{bmatrix} \sum g_i x_i & \sum g_i y_i \\ \sum h_i x_i & \sum h_i y_i \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \sum g_i (s + K_i - l_i^2) \\ \sum h_i (s + K_i - l_i^2) \end{bmatrix}, \tag{28}$$

where,

$$s = x^2 + y^2, \quad K_i = x_i^2 + y_i^2, \tag{29}$$

$$g_i = \frac{x - x_i}{\sigma_i^2 r_i (r_i + l_i)},\ h_i = \frac{y - y_i}{\sigma_i^2 r_i (r_i + l_i)}, \tag{30}$$

with (x, y) the receiver estimated location and (x_i, y_i) the location of each emitter.

In an AML algorithm, there is at least one $\boldsymbol{\Theta}$ which corresponds to the minimum value of J. For that reason, the AML can provide a position estimate when only two measurements are available. The lack of synchronisation leads to a wider uncertainty region. However, in this paper, the problem is solved by computing the value of J for the entire grid. The global minimum and a local minimum closest to the mean location of the emitters is used to compare the performance of estimation of $\boldsymbol{\Theta}$. This offers a baseline of how good the AML can performe, when iteratively solving 28.

II. Results

Table I provides the most relevant parameters used throughout the simulations. The SCF was estimated using the fast Fourier transform accumulation method (FAM) [11], [21].

A. Probability of detection

Fig. 5 shows the probability of detection for OFDM signals versus the signal to noise ratio (SNR), considered as the ratio between signal and noise powers.

Fig. 5 compares hypotheses $\mathcal{H}_{1.1}$ through $\mathcal{H}_{1.3}$. The probability is obtained by counting how many times K, $K = 5$, cyclic frequencies are observed in the SCF, for each simulation iteration. The total number of simulation iterations is present in Table I. The noise-only case has been omitted since its probability is close to zero.

Similar results have been obtained for CDMA signal detection, the only observed exception was that the CDMA signal curves start at a lower SNR level (-3 dB).

B. Positioning performance

Table II and Table III provide results on the expected performance of the proposed architecture. These tables contain the root mean square error (RMSE) over 10^4 iterations in a

TABLE I
SIMULATION PARAMETERS

Common parameters	
Number of random trials, T	5000
Activity threshold, V_{th}	0.75
Observation time	2 ms
Cyclic resolution, $\Delta\alpha$	0.5 μHz
Window length, ϵ	$100\Delta\alpha$
Frequency resolution	0.1 Hz
Sampling frequency, f_s	40 MHz
Receiver filter bandwith, B_T	20 MHz
CDMA parameters (IEEE 802.11b)	
Modulation	DQPSK
Chip rate, f_c	11 MHz
Data rate, f_b	2 MHz
Spreading Sequence	Barker code (11 chips), [22], [23]
OFDM parameters	
Modulation	16-QAM
Number of carriers, N	64
Symbol period, T_{symbol}	4 μs
Sub-carrier spacing, Δ_f	$B/N = 312.5$ kHz
Guard interval, T_{gi}	$\Delta_f^{-1}/4$ s
Useful symbol period, T_U	Δ_f^{-1} s
Pilot power boost	+3 dB [24]
Bandwith	20 MHz

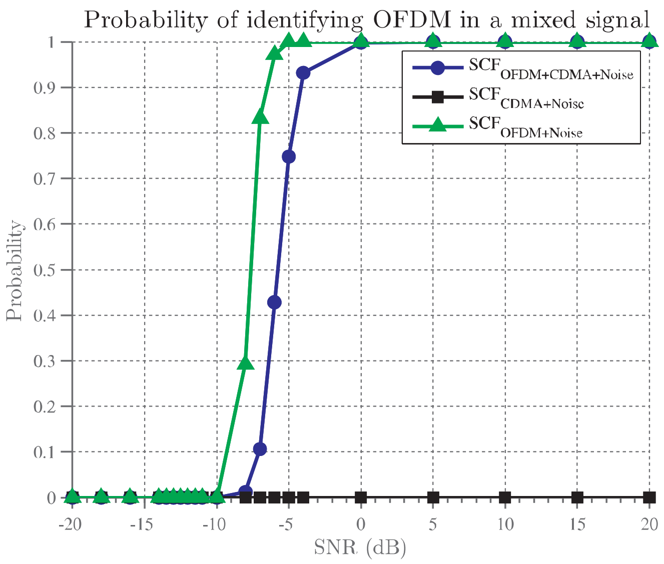

Fig. 5. Probability of detection under $\mathcal{H}_{1.1} - \mathcal{H}_{1.3}$.

25 by 25 m square room. In every iteration the emitters and user positions were obtained from an uniform distribution. To simplify the problem, it was considered that the CDMA and OFDM sytems were synchronised among each other, but a clock bias to the receiver is still present. This bias was assumed to be bigger for OFDM emitters. The position estimate is taken in Table II as the global minimum and in Table II as the local minimum closest to the mean location of the emitters.

In both tables, the addition of more emitters, in general, leads to an accuracy improvement, eg, over the diagonal of the tables. In some cases, the addition of more emitters,

TABLE II
ROOT MEAN SQUARE ERROR FOR AML ALGORITHM, WITH $\sigma_{CDMA} = 1$ AND $\sigma_{OFDM} = 10$ OVER 10^4 RUNS INSIDE A 25×25 M GRID AND A CLOCK BIAS OF 2 AND 8 M RESPECTIVELY. GLOBAL MINIMUM CONSIDERED FOR THE POSITION ESTIMATE.

RMSE (m)		**Number of OFDM emitters** $N_{BS_{OFDM}}$					
		0	**1**	**2**	**3**	**4**	**5**
Number of CDMA emitters $N_{BS_{CDMA}}$	**0**	-	-	11.82	10.97	10.26	9.74
	1	-	**9.56**	8.56	7.96	7.78	7.51
	2	**5.90**	**5.82**	**5.53**	**5.47**	**5.47**	**5.54**
	3	3.60	3.85	4.00	**4.10**	4.19	4.21
	4	**2.95**	**3.12**	**3.31**	**3.38**	**3.52**	**3.63**
	5	2.70	2.83	2.95	3.05	3.17	**3.31**

TABLE III
ROOT MEAN SQUARE ERROR FOR AML ALGORITHM, WITH $\sigma_{CDMA} = 1$ AND $\sigma_{OFDM} = 10$ OVER 10^4 RUNS INSIDE A 25×25 M GRID AND A CLOCK BIAS OF 2 AND 8 M RESPECTIVELY. MINIMUM TAKEN AS THE CLOSEST TO THE MEAN BASE STATIONS POSITIONS

RMSE (m)		**Number of OFDM emitters** $N_{BS_{OFDM}}$					
		0	**1**	**2**	**3**	**4**	**5**
Number of CDMA emitters $N_{BS_{CDMA}}$	**0**	-	-	10.78	9.72	8.85	8.23
	1	-	**7.37**	7.32	6.68	6.33	5.97
	2	**5.74**	**4.91**	**4.56**	**4.37**	**4.30**	**4.27**
	3	3.31	3.22	3.15	**3.13**	3.15	3.15
	4	**2.46**	**2.42**	**2.50**	**2.50**	**2.56**	2.60
	5	2.08	2.12	2.17	2.18	2.24	**2.33**

especially with noisy OFDM emitters, seems to lead to a higher RMSE (see the values along the diagonal of the tables). However, most of these differences are quite small, which means it is safe to assume that by adding more noisy emitters the performance should improve or remain approximately the same.

III. CONCLUSION

This paper proposes a cognitive positioning architecture for CDMA and OFDM signals. The architecture relies on a spectrum sensing block to detect the presence of CDMA and OFDM signals in the surrounding spectrum. The proposal suggests the use of cyclostationary algorithms to distinguish the signals present in an unique digital representation. The paper provides results that show how such signals could be distinguished, by suggesting a simple detection and decision algorithm. This detection would be useful to activate only the required acquisition loops, allowing the receiver to save energy and computational resources.

After a successful characterisation of the spectral contents, the cognitive positioning system utilises this information to extract from the signals timing information to compute TOA measurements. After that, assuming the locations of the emitters to be known, an AML algorithm combines the information from several SoO emitters. The performance of the algorithm was studied by comparing the estimate obtained from the global minimum and the minimum closest to the mean location of the emitters over the entire grid space.

In the end, the goal of this architecture is to use the cognition layers appearing in future communications standards and use this information to improve user positioning and resource management of the mobile devices.

Acknowledgment

This work was financially supported by EU FP7 Marie Curie Initial Training Network MULTI-POS (Multi-technology Positioning Professionals) under grant nr. 316528.

The authors express their gratitude to the Academy of Finland (project 256175 "Cognitive Approaches for Location in Mobile Environments") for its additional financial support for this research work.

References

[1] J. Mitola and G. Maguire, "Cognitive Radio: Making Software Radios More Personal," in *IEEE Pers. Commun.*, vol. 6, no. 4, 1999, pp. 13–18.

[2] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Commun. Surv. Tutorials*, vol. 11, no. 1, pp. 116–130, 2009.

[3] H. Celebi and I. Guvenc, "Cognitive-radio Systems for Spectrum, Location, and Environmental Awareness," *IEEE Antennas Propag. Mag.*, vol. 52, no. 4, pp. 41–61, 2010.

[4] C.-I. Badoi, N. Prasad, V. Croitoru, and R. Prasad, "5G Based on Cognitive Radio," *Wirel. Pers. Commun.*, vol. 57, no. 3, pp. 441–464, Jul. 2010.

[5] H. Celebi and H. Arslan, "Utilization of Location Information in Cognitive Wireless Networks," *IEEE Wirel. Commun.*, no. August, pp. 6–13, 2007.

[6] E. S. Lohan, J. Lundén, G. Seco-Granados, V. Koivunen, T. Potential, W. A. Cognitive, and P. Framework, "Cyclic frequencies of GNSS signals and their potential within a cognitive positioning framework," *ION J. Navig.*, 2013.

[7] R. Exel, "Carrier-based ranging in IEEE 802.11 wireless local area networks," in *2013 IEEE Wirel. Commun. Netw. Conf.* IEEE, Apr. 2013, pp. 1073–1078.

[8] M. Shafiee, "WiFi-based Fine Timing Assistance for GPS Acquisition," http://theses.ucalgary.ca/handle/11023/1101, 2013.

[9] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of wireless indoor positioning techniques and systems," *IEEE Trans. Syst. Man Cybern.*, vol. 37, no. 6, pp. 1067–1080, 2007.

[10] D. Zhang, F. Xia, and Z. Yang, "Localization technologies for indoor human tracking," in *Int. Conf. Futur. Inf. Technol.*, no. 60903153, Busan, 2010. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5482731

[11] W. A. Gardner, A. Napolitano, and L. Paura, "Cyclostationarity: Half a Century of Research," *Signal Processing*, vol. 86, no. 4, pp. 639–697, Apr. 2006.

[12] T. Fusco, L. Izzo, A. Napolitano, and M. Tanda, "On the second-order cyclostationarity properties of long-code DS-SS signals," *IEEE Trans. Commun.*, vol. 54, no. 10, pp. 1741–1746, Oct. 2006.

[13] P. Sutton, K. Nolan, and L. Doyle, "Cyclostationary Signatures in Practical Cognitive Radio Applications," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 13–24, Jan. 2008.

[14] J. Lunden and V. Koivunen, "Spectrum Sensing in Cognitive Radios Based on Multiple Cyclic Frequencies," in *Cogn. Radio Oriented Wirel. Networks Commun.*, 2007.

[15] E. Guenterberg, H. Ghasemzadeh, R. Jafari, and R. Bajcsy, "A Segmentation Technique Based on Standard Deviation in Body Sensor Networks," in *Eng. Med. Biol. Work.*, 2007.

[16] A. Benbasat and J. Paradiso, "An Inertial Measurement Framework for Gesture Recognition and Applications," in *Gesture Sign Lang. Human-Computer Interact.*, 2002.

[17] H. O. Lancaster and E. Seneta, *Chi-Square Distribution*. John Wiley & Sons, Ltd, 2005. [Online]. Available: http://dx.doi.org/10.1002/0470011815.b2a15018

[18] P. Williams, "Evaluating the state probabilities of M out of N sliding window detectors," http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA348378, DSTO Aeronautical and Maritime Research Laboratory, Tech. Rep., 1998.

[19] Y. Chan, "Exact and approximate maximum likelihood localization algorithms," *IEEE Trans. Veh. Technol.*, vol. 55, no. 1, pp. 10–16, 2006. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1583909

[20] H. Sayed, A. Tarighat, and N. Khajehnouri, "Network-Based Wireless Location," *IEEE Signal Process. Mag.*, no. July 2005, pp. 24–40, 2005.

[21] R. Roberts, W. Brown, and H. Loomis, "Computationally Efficient Algorithms for Cyclic Spectral Analysis," *Signal Process. Mag. IEEE*, 1991.

[22] L. A. N. Man, S. Committee, and I. Computer, *Part 11 : Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications IEEE Computer Society*, 2012, vol. 2012, no. March.

[23] T. Lee and A. Al-Banna, "Spectral Signatures and Interference of 802.11 Wi-Fi Signals with Barker Code Spreading," *New Front. Dyn. Spectr. Access Networks*, no. 1, pp. 672–675, 2005.

[24] S. R. Schnur, "Identification and Classification of OFDM Based Signals Usng Preamble Correlaton and Cyclostationary Feature Extraction," Master thesis, Naval Postgraduate School, 2009.