

Spectrum Agile Radio: Detecting Spectrum Opportunities

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Abstract— The opening up of the unlicensed bands for commercial use has been a tremendous success. Wireless communications in computing, mobile, medical and consumer electronics market segments have grown rapidly in the past few years. Due to this success, radio resources in the unlicensed bands are progressively becoming scarce. Recently, the Spectrum Policy Task Force (SPTF) within the FCC has recommended that the FCC regulate spectrum allocation based on market principles. Such regulation implies radio networks wherein radios sense their environment and make opportunistic use of available radio resources while not interfering with the operation of existing licensed networks. In this paper, we focus on a key component of such Spectrum Agile Radio (SARA) systems, namely, the detection of spectrum opportunities. We present results of simulation studies of the use of Hough Transform and autocorrelation function for the detection of spectrum opportunities.

Keywords— Spectrum Agile Radio, Opportunity Identification, Hough transform, IEEE 802.11k Radio Resource Measurement

I. INTRODUCTION

The increasing popularity of radio communication networks over the last years, and of wearable, hand-held computing and communicating devices, as well as consumer electronics, indicates that there will be an ever increasing demand for radio communication networks providing high capacity communication. Considering this increase in demand, it is clear that the necessary radio spectrum will not be available in the future, due to the limited nature of radio resources. Today, consumer electronics radio communication systems operate mainly in unlicensed bands. Radio resources in the unlicensed bands are therefore often efficiently used [1]. However, most of the radio spectrum is allocated by traditional licensed radio services, and often not used at all. With the current FCC approach to regulation, radio spectrum resources are often not efficiently used.

This problem is approached by Spectrum Agile Radio (SARA) systems. SARA makes use of the licensed radio spectrum in an opportunistic way, controlled by SARA policies. A SARA device seeks opportunities, i.e. unused radio resources prior to communicating, and then communicates using the identified opportunities without interfering with the operation of licensed radio networks. Therefore, a key mechanism of SARA

is to identify opportunities to communicate, and to identify other, competing radio systems. SARA systems will work with evolving FCC regulations for radio spectrum allocation that are based on Spectrum Policy Task Force (SPTF) recommendations [2].

Approaches to SARA are discussed in the context of Next Generation (XG) framework [3].

To facilitate the rollout of SARA, it should be built on top of existing radio communication standards such as IEEE 802.11 with its recent extensions for radio resource management [4]. Therefore, we discuss the emerging supplement standard to the popular IEEE 802.11 wireless Local Area Network (LAN) for radio resource measurements, namely IEEE 802.11k [5]. We discuss measurements based on the carrier sensing, i.e., Clear Channel Assessment (CCA), and approaches for spectrum opportunity identification from the obtained measurement results.

II. RADIO RESOURCE MEASUREMENT IN IEEE 802.11k

IEEE 802.11 Task Group k (TGk) was formed in January 2003 to develop extension to IEEE 802.11 wireless LAN specification for radio resource measurement. This extension will specify the types of radio resource information to measure and the request/report mechanism through which the measurement demands and results are communicated among stations.

The goal of TGk is to provide tools by which a radio station can measure and assess the radio environment and take corresponding actions. To fulfill this goal, the current TGk draft defines seven types of measurements [5]:

- In Beacon report, a measuring station reports the beacons or probe response it receives during the measurement period.
- In Frame report, a measuring station reports information about all the frames it receives from other stations during the measurement period.
- In Channel Load report, a measuring station reports the fractional duration over which CCA indicates the channel is busy during the measurement period.

- In Noise Histogram report, a measuring station reports non-802.11 energy by sampling the channel only when CCA indicates that no 802.11 signal is present.
- In Hidden Node report, a measuring station reports the identity and frame statistics of hidden nodes detected during the measurement period.
- In Medium Sensing Time Histogram report, a measuring station reports the histogram of medium busy and idle time observed during the measurement period.
- In Station Statistic report, a measuring station reports its statistics related to link quality and network performance during the measurement period.

The measurements in TGk enable an IEEE 802.11 radio network to collect information of neighboring access points (via Beacon report) and information on link quality to neighbor stations (via Frame report, Hidden Node report and Station Statistic report). The tool set also provides ways to find out interference level (via Noise Histogram report) and medium load statistics (via Channel Load report and Medium Sensing Time Histogram report).

Those are useful information for a station to collect when assessing its radio environment. However, none of the measurement enables the station to identify future opportunities to use the medium. Ways to identify spectrum opportunities, and other interfering radio systems, are therefore discussed in the following.

III. SPECTRUM OPPORTUNITY IDENTIFICATION

As indicated in earlier sections, when *radio networks* encounter *other devices* that emit energy (and therefore use shared radio resources) in their vicinity, it is desirable to characterize the radio resource usage patterns of these other devices. Such a characterization of the usage patterns results in the identification of opportunities for the radio networks.

Other devices referred to previously includes radars, which are primary emitters, or other radio networks, which are secondary emitters.

III-1 Autocorrelation

A classical approach to determine periodic occurrences of spectrum opportunities, or radar pulses is based on the autocorrelation function. The sequence of CCA events obtained through listening to the channel, is processed with the autocorrelation function. Periods in the channel conditions are indicated by local maxima in the resulting function.

III-2 Hough Transform

In this section we will examine the use of Hough Transform for the detection of radar pulses as an example for any type of radio signals that create periodic patterns. We will use a version of the Hough Transform, known as Randomized Hough Transform (RHT) to detect the parameters of helices wrapped around cylinders, as explained later in the section. The Hough Transform [6] has been studied in image processing literature

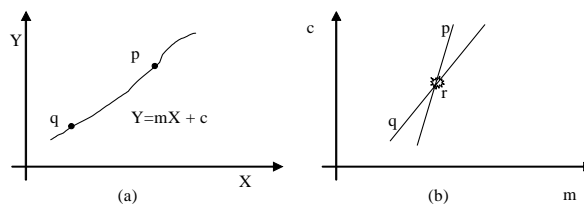


Fig. 1: Hough Transform used to detect straight lines (a) image space and (b) parameter space.

for detection of patterns such as lines, circles and ellipses in binary images. The effectiveness of Hough Transform in detecting patterns in data with many overlaying patterns and random noise is proven in [6]. In the presence of outliers, the Hough Transform is more robust than least squares estimation.

In brief, the Hough Transform is used to transform data from image space to an accumulator (or histogram) in parameter space, as shown in Fig. 1.

The image space is represented by (x, y) , whereas, the parameter space is represented by $(\text{slope}, \text{intercept})$, that is (m, c) . For each point in the image space (e.g. p and q), a line is generated in the parameter space as shown. The parameter space can be seen as a two dimensional histogram. A peak, r , in the parameter space corresponds to a line in the image space. The Hough Transform is robust because in the image space, a collection of collinear points is enough to result in a peak in the parameter space. However, it has the drawback that the parameter space could require large amount of memory in the computer. To address this drawback the RHT was developed [7]. The RHT as applied to straight-line detection, results in randomly picking pairs of points and computing and accumulating a parameter (for instance, slope). When enough confidence in the peak is achieved, the process stops, thus reducing both memory and processing time.

The use of Hough Transform for radar pulse detection was first studied in [8]. The original radar pulse train is a 1-D signal.

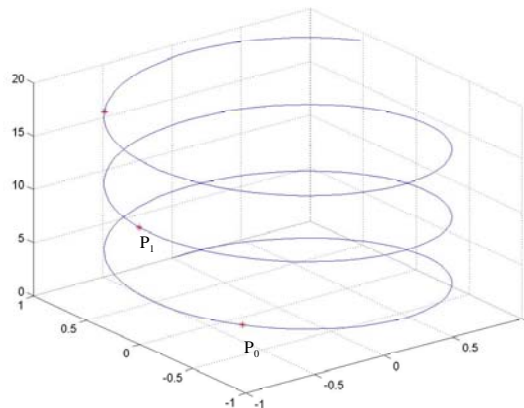


Fig. 2: A helix given by the Eq. (1), for $\varpi = 1$.

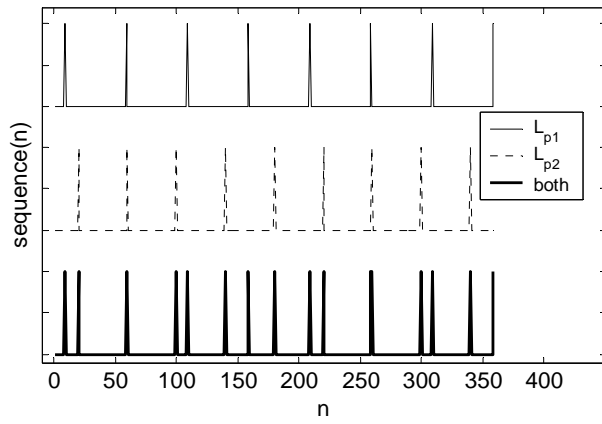


Fig. 3: Discrete sequence vector used for evaluation.

The authors have used 1-D to 2-D transformation (like a raster scan) and then applied the Hough Transform to detect straight lines, which correspond to pulse trains. Furthermore, they have computed the noise floor. We extend their work by first transforming the 1-D signal to a 3-D helical signal, and apply RHT to it. A helix may be represented by the following parametric equations:

$$\begin{aligned} X(t) &= \sin(\omega t) \\ Y(t) &= \cos(\omega t) \\ Z(t) &= t \end{aligned} \quad (1)$$

This helix is cylindrical (as opposed to the more general elliptical) and has unit radius. Based on the parameter ω a new helix can be generated that wraps around the cylinder more slowly as ω decreases. In Fig. 1, the points (marked with *) on the helix themselves form a helix, with an ω value less than one. Given two points on the helix $P_0(x_0, y_0, z_0)$ and $P_1(x_1, y_1, z_1)$, the parameter ω can be given by the following equation:

$$\omega = \frac{a \tan\left(\frac{y_1}{x_1}\right) - a \tan\left(\frac{y_0}{x_0}\right)}{z_1 - z_0} \quad (2)$$

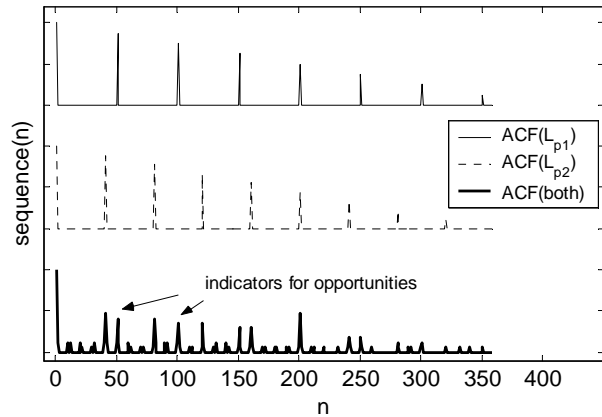


Fig. 4: Autocorrelations (right hand side) of the three sequences.

If the two points P_0 and P_1 are inside one whorl of the helix, then ω works out to be 1. The length of the line segment given by one twirl of helix is given in Eq. (3).

$$l = 2\pi \cdot \sqrt{1 + \left(\frac{1}{\omega}\right)^2} \quad (3)$$

IV. EVALUATION AND BASIC CONCEPTS

We discuss the RHT and the autocorrelation approach separately in the following.

IV-1 Randomized Hough Transform

Let us represent the location (time-of-arrival) of the radar pulse train with the discrete sequence vector L_p . The sequence $L_{p1} = [9, 59, 109, 159, 209, 259, 309, 359]$ is shown in Fig. 3, top sequence. The corresponding right-hand side of the autocorrelation function is indicated in Fig. 4, top sequence. For this sequence, the ω histogram as indicated in Fig. 5 is obtained by the Hough Transform. For this case, $\omega = 0.116$. Now let us consider the case where there are two pulse trains that are multiplexed and represented by $L_{p2} = [9, 20, 59, 60, 100, 109, 140, 159, 180, 209, 220, 259, 260, 300, 309, 340, 359]$, as illustrated in Fig. 3, bottom sequence.

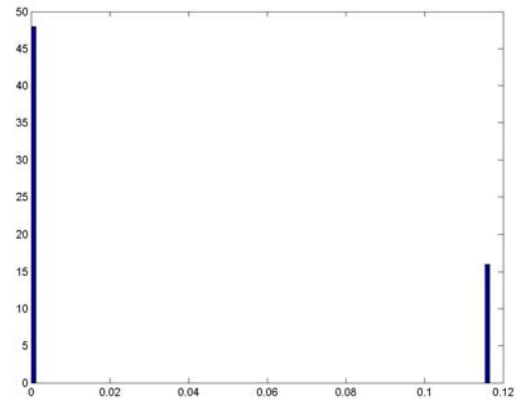


Fig. 5: Histogram of ω for L_{p1}

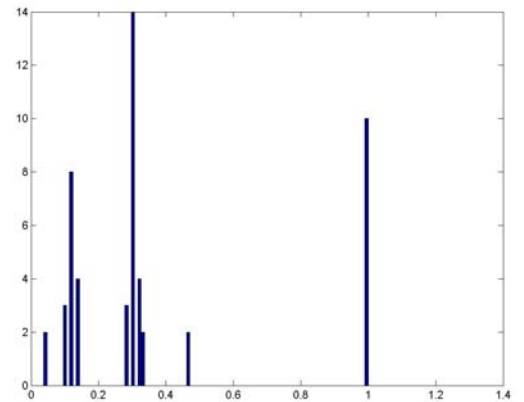


Fig. 6: Histogram of ω for L_{p2}

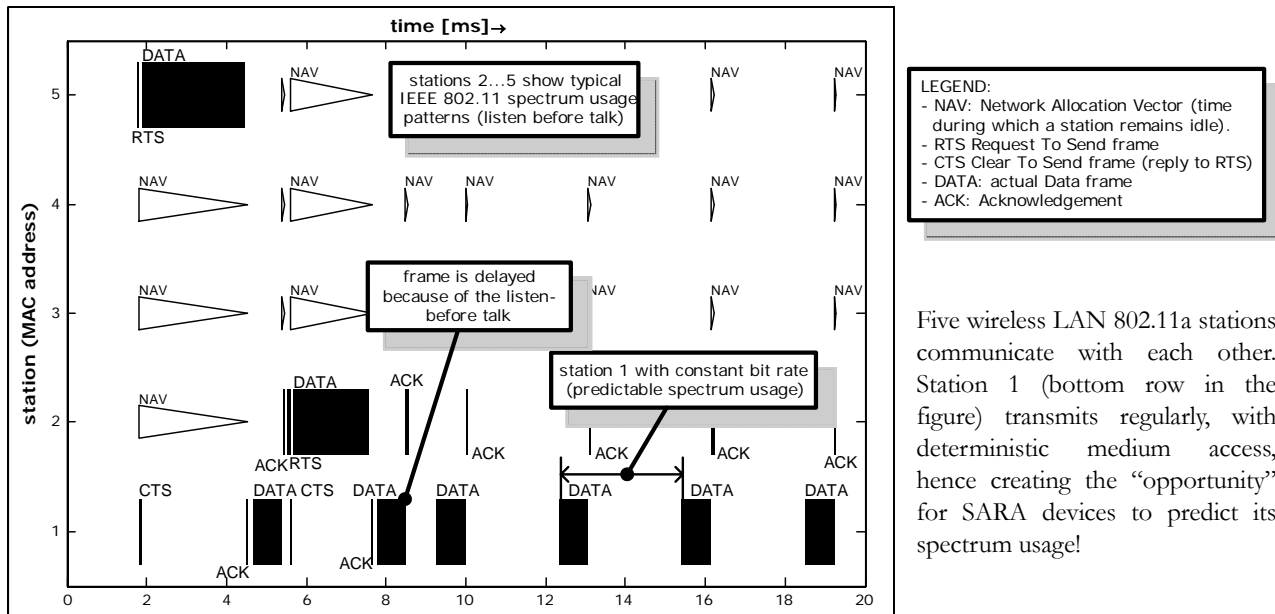


Fig. 7: Spectrum usage pattern for wireless Local Area Network (LAN) IEEE 802.11a (5GHz unlicensed band).

The corresponding right-hand side of the autocorrelation function is indicated in Fig. 4, bottom sequence. The ϖ histogram as indicated in Fig. 6 is obtained by the Hough Transform of this multiplexed sequence. Note that $\varpi = 1$ corresponds to points on the helix within one whorl.

The advantage of the autocorrelation function, namely, its notional simplicity has to be balanced with its disadvantage, namely computational complexity. Similarly, for the Hough Transform, its advantage of computational simplicity and robustness has to be balanced with its disadvantage namely possible dependence on the choice of parameters.

IV-2 Autocorrelation Function

Fig. 7 illustrates a typical spectrum usage pattern of IEEE 802.11a, when five stations communicate. The dark solid fields illustrate frame transmissions, the triangles illustrate timers that are set by the individual stations. Station 1 carries a traffic that offers a constant bit rate, and hence produces a deterministic spectrum usage pattern, because the intervals between consecutive frame exchange attempts that are initiated by station 1 do not change over time. However, the medium is busy when other stations transmit, and during busy times, station 1 does not access the medium, because of the nature of the listen-before talk based medium access control protocol in IEEE 802.11. Apparently, the autocorrelation function is suitable to determine the deterministic medium accesses, and to assess what the period of the medium access is. This is illustrated in Fig. 8 and Fig. 9. In these figures, a spectrum usage pattern similar to the one in Fig. 7 is illustrated (bottom graph in the two figures, the deterministic medium access occurs every 20 ms and is embedded in other random frame exchanges), and the corresponding autocorrelation functions (top graph in the two figures). It can be seen how the deterministic medium access is identified. The difference between the figures lies in the length of the measurement duration: whereas for the identification of spectrum opportunities, in Fig. 8 the measurement duration was 1000 ms, the measurement duration for Fig. 9 was only 100 ms. Spectrum opportunities, i.e., significant local maxima in the autocorrelation function, are indicated. For better comparison, in both figures the first 100 ms of the measured CCA patterns are shown. When comparing the two figures, it can be seen that with the longer measurement durations, spectrum opportunities are more reliably identified, at the cost of higher computation effort, and longer measurement durations.

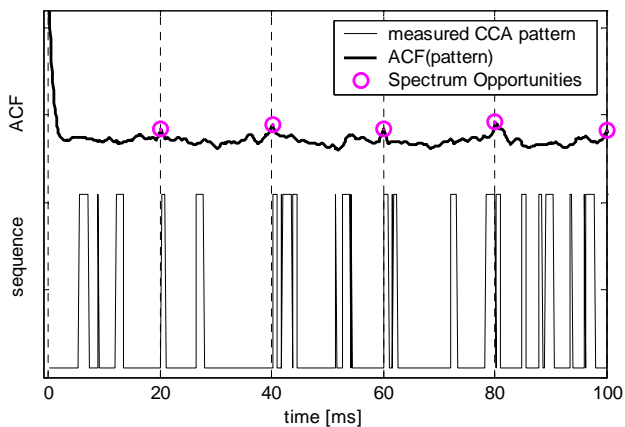


Fig. 8: The first 100ms of the spectrum usage pattern (bottom) and corresponding ACF, for a measurement duration of 1000ms. The “Spectrum Opportunities” indicate the detection of deterministic spectrum usages.

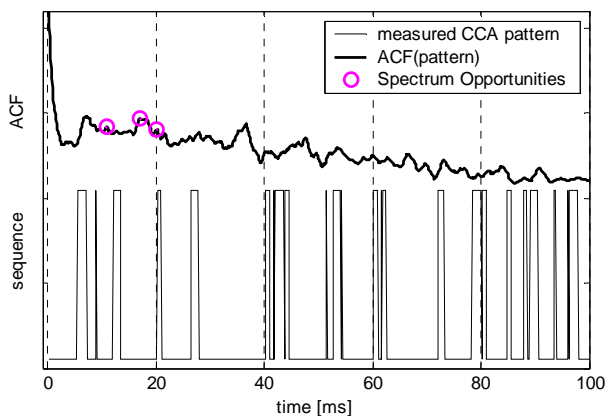


Fig. 9: Spectrum usage pattern (bottom) and corresponding ACF. Measurement duration: 100ms.

V. CONCLUSION

We have outlined and compared two approaches for spectrum opportunity identification, and radio system identification, based on the CCA mechanism of IEEE 802.11. We use the autocorrelation of the sequence of CCA events as well as the random Hough transform of the data. We have shown that introducing this type of measurement into IEEE 802.11 (for example as part of 802.11k), provides a first step towards Spectrum Agile Radio. In the future, the two methods described to identify periodic accesses to the radio spectrum may be associated with each other in order to increase the precision and accuracy. We expect that both alternatives show advantages and disadvantages in different scenarios, and a combination of both may therefore result in the most precise identification of other radio systems.

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