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Channel Usage Classification Using Histogram-Based Algorithms for Fast Wideband Scanners

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Abstract

The paper presents a set of histogram-based algorithms to determine the wireless channel usage or station occupancy of fixed frequency channels.

The results of this study show the effectiveness of using the histogram-based algorithms to analyze and estimate the channel usage with a significantly small number (down to 25) of scanned samples. Both simulated and measured data sets were processed and their results show significant accuracy for various scenarios, including the line-of-sight (LOS) and multipath frequency modulation (FM) signal cases. However, the results of the LOS amplitude modulation (AM) signal cases show multiple peaks in the signal-to-noise ratio (SNR) histograms due to the amplitude variation of the AM signals. Thus, the histogram-based algorithms in this study solely cannot be used to classify the channel usage of the LOS AM cases. The AM type and its characteristics have to be identified first by other algorithms. Then the averaged AM results from the histogram-based algorithms can be used as estimates for classification.

In general, the histogram-based algorithms provide a simple and efficient way to classify the LOS channel usage. The approach is particularly applicable for fast wideband scanning devices where items such as power levels, SNRs, angles of arrival (AOAs) and AOA instantaneous standard deviations (ISDs, that is, SDs at each scan) from several channels are reported per second.

I. Introduction

For each transmitter-receiver scenario, a wideband scanning device such as the CRC's Spectrum Explorer (SE) [1] could be used to scan, collect and preprocess wireless signals to form a channel data set. The wideband nature of the scanner allows several channel measurements to be taken in a short period. Each channel may have multiple users from various AOAs with different SNRs. Users may use various modulations such as AM, FM, etc. Each channel data set resulting from the preprocessing by the scanning device may include information such as power levels, SNRs, AOAs and AOA ISDs. The preprocessed SNR, AOA and AOA ISD samples are used to generate related histograms for active channels. Statistically, each lobe of a variable histogram from various scans is linearly related to the distribution density of that variable, given that the number of scans is large enough [2]. Thus, those histograms provided valuable information of related signals. The purpose of this study is to develop a set of histogram-based algorithms to determine the wireless channel usage or the station occupancy of a fixed frequency channel.

II. Concept and Algorithms

The results presented in [3] make the assumption that the channel impulse response $h(t,\theta)$ as a function of time and azimuth angle is a separable function, or

$$h(t,\theta) = h(t)h(\theta)\ , \tag{1}$$

where $h(t)$ is the time domain impulse response, and

$$h(\theta) = \sum_{l=0}^{\infty}\sum_{k=0}^{\infty} \beta_{kl}\,\delta(\theta - \Theta_l - \omega_{kl})\ , \tag{2}$$

is the angular domain impulse response, where β_{kl} is the received signal amplitude of the *k*th arrival in the *l*th cluster, Θ_l is the mean azimuth AOA of the *l*th cluster, and ω_{kl} is the azimuth AOA of the *k*th arrival in the *l*th cluster, relative to Θ_l. In this study, for non-amplitude-varying signals (like FM), the number of AOA clusters (histogram lobes) corresponds to the number of transmitters and the number of arrivals within an AOA histogram lobe corresponds to the potential multipath effect, given the assumption that the AOA histogram lobes are distinct. This study doesn't include the multi-user scenarios where both the AOA and SNR histogram lobes are not distinct.

Since there is a quasi-linear relationship between the power levels and SNRs, the SNR histogram is linearly related to the histogram of power levels which are proportional to energy levels, given the assumption of additive white Gaussian noise. From [4] and [5], the cluster energy is linearly related to the relative delay of signals, assuming that all incident waveforms are identical. Thus, the relative delay of signals is linearly related to SNRs. That is, the lower the SNRs are estimated, the farther apart the transmitters (users) are located, assuming the same transmitted power level is used. For amplitude-varying signals (like AM), the effect of intra-signal amplitude variation also needs to be considered.

The SNR, AOA and AOA ISD histograms from the SE's preprocessed data were generated from 1000 scans for various scenarios. Note that the AOA and AOA ISD histograms were only generated for each valid SNR histogram lobe (lobe_peak/*HistSNR*_peak > 0.8). For a SNR histogram, its isolated lobes *CS(M,3)* were found where *M* is the final grouped lobe number; *CS(k,1 to 3)* are the leftmost, peak and rightmost sample indices of the *k*th pre-lobe. For each *k*, the pre-lobes are grouped to *M* lobes using the (Matlab) algorithm:

```
if (CS(k,3)-CS(k,2))<=2; if CS(k+1,2)-CS(k,2)<3
  if HistSNR(CS(k,2))>=HistSNR(CS(k+1,2));CS(k,3)=CS(k+1,3);
  else CS(k,2)=CS(k+1,2); CS(k,3)=CS(k+1,3); end; end; end.
```

The purpose of this grouping operation is to distinguish distinct clusters that are taken to represent separate transmitters.

The averaged ISD (AISD) was obtained by weight averaging the AOA ISD histogram lobe. The weight average of a histogram lobe is:

$$WA = \sum_{m=m_s}^{m_e}[m \times Hist(m)] \Big/ \sum_{m=m_s}^{m_e} Hist(m)\,, \tag{3}$$

where m_s, m_e are the start and end sample indices within a histogram lobe, respectively.

For an AOA histogram, its isolated lobes *CA(N,3)* were found where *N* is the final grouped lobe number; *CA(k,1 to 3)* are the leftmost, peak and rightmost sample indices of the *k*th pre-lobe. For each *k*, the pre-lobes are grouped to *N* lobes using the (Matlab) algorithm:

```
if (CA(k,3)-CA(k,2))<AISD
 if HistAOA(CA(k,2))>HistAOA(CA(k+1,2));CA_C(k,1)=CA(k,1);
    CA_C(k,2)=CA(k,2); CA_C(k,3)=CA(k+1,3);
 else CA_C(k,1)=CA(k,1); CA_C(k,2)=CA(k+1,2);
    CA_C(k,3)=CA(k+1,3); end; n_cc=2; n_rc=N'-n_cc;
 while (CA_C(k,3)-CA_C(k,2)<=2*AISD)&n_rc>0
        if HistAOA(CA(n_cc+1,2))<=HistAOA(CA_C(k,2))
          CA_C(k,3)=CA(n_cc+1,3);
        else CA_C(k,2)=CA(n_cc+1,2); CA_C(k,3)=CA(n_cc+1,3);
        end; n_cc=n_cc+1; n_rc=N'-n_cc; end;
elseif CA(k+1,2)-CA(k+1,1)<=AISD
       if HistAOA(CA(k+1,2))>=HistAOA(CA(k,2))
CA_C(k,1)=CA(k,1);CA_C(k,2)=CA(k+1,2);CA_C(k,3)=CA(k+1,3);
       elseif  HistAOA(CA(k+1,2))<HistAOA(CA(k,2))
CA_C(k,1)=CA(k,1);CA_C(k,2)=CA(k,2);CA_C(k,3)=CA(k+1,3);
       end; end;
CA(k,1)=CA_C(k,1);CA(k,2)=CA_C(k,2);CA(k,3)=CA_C(k,3); end;
```

where *N'* is the grouped lobe number computed on the fly. Again, the goal is to distinguish separate clusters and therefore different transmitters. The standard deviations (SDs) of AOAs were then calculated from the isolated AOA histogram lobes.

Each valid SNR histogram lobe was processed independently. The weight average of each valid SNR histogram lobe is an estimate of the actual SNR of the detected signal. Within each valid SNR histogram lobe, the angularly weighted average of each valid AOA histogram lobe (lobe_peak/*HistAOA*_peak > 0.5) is an estimate of the actual AOA of the detected signal. The angularly weighted average (in degree) of a histogram lobe is:

$$AWA = \frac{180}{\pi} \times Ang\left[\sum_{m=m_s}^{m_e} e^{j\frac{\pi}{180}[m \times Hist(m)]}\right], \tag{4}$$

where $Ang[\bullet]$ represents the phase angle of $\bullet$ in radians. Again, m_s, m_e are the start and end sample indices within a histogram lobe, respectively.

The estimated pair (SNR, AOA) represents an estimated signal from a transmitter (user) within an active channel. A user has to be detected in a channel most of the time (50% in this study) among scans for that channel to qualify as an active channel.

III. Simulated and CRC-measured Data

The simulated data of the SE's preprocessed results were generated using Matlab for 1000 scans. Normal distributions were used with various seeds for each trial as the signal models of the SNRs and AOAs to form the internal data sets.

The CRC-measured data were obtained using the SE to scan, collect and preprocess the FM and AM signals within various frequency bands in various scenarios. The FM voice signal was within 3 bands (30~90, 460~470 and 902~928 MHz) and had 15 kHz peak frequency deviations. The AM digital random sequence signal was within 902~928 MHz with 3.6 kHz bandwidth and used 60% modulation index. A single transmitter/receiver (TX/RX) pair was used for each scenario. Some scenarios were clear LOS, some were with the transmitter near a building and some with the receiver near trees. The multipath effect could be observed among scenarios. For each scenario, the height of the receiver was either low (about 8 feet above ground) or high (about 25 feet above ground) while the height of the transmitter was always low. For scenarios 1 to 6, the receiver was located at the origin (0°, 0 meter). For scenario 7, the transmitter was located at the origin. The location information of each scenario is shown in TABLE I and Fig. 1. For each scenario, around 5000 data scans were collected by the SE with about 300 ms between consecutive scans. For each scan, only one 25 kHz channel was used. The channel and the CRC-transmitted signal used the same frequency center. The data collected within each channel were preprocessed using a 2.5 kHz FFT resolution (400 μs time span for each scan) to determine the SNRs, AOAs and AOA ISDs of every detected channel.

TABLE I. CRC-MEASURED SCENARIOS

Scenario	TX Location (degrees, meters)	Description
1	(0, 110)	Clear LOS
2	(108, 100)	Clear LOS
3	(340, 110)	Clear LOS
4	(16.5, 110)	Clear LOS
5	(33, 110)	Clear LOS
6	(122, 300)	Beside a building
	RX Location (degrees, meters)	
7	(10, 350)	Behind 20' high trees

For a channel to be deemed active, it had to be detected more than 500 times during the first 1000 scans. For each active channel, the corresponding SNRs, AOAs and AOA ISDs from the 1000 scans were gathered to form the internal data sets.

For both of the simulated and CRC-measured data, once the internal data sets were obtained, various histograms were generated from the samples of the SNRs, AOAs and AOA ISDs. The results included estimated SNR (E_S in dB), estimated AOA (E_A in degrees), AOA AISD (AI_A in degrees) and AOA SD (SD_A in degrees) vs. SNR in dB.

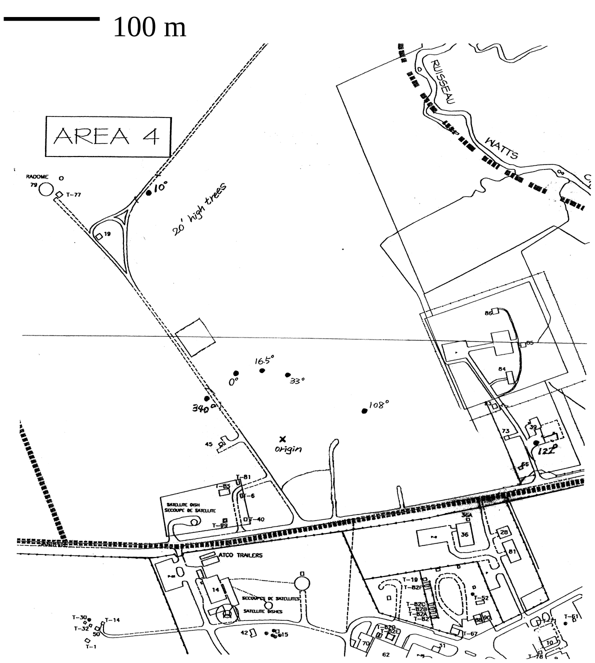

Fig. 1. Map for CRC-measured scenarios

IV. Selected Results

Simulated Test Scenario: Three signals, 20° AOA with 2° SD for signal one, 40° AOA with 3° SD for signal two, 60° AOA with 4° SD for signal three, 5 to 40-dB SNRs with 2-dB SD for each signal. The SNR and AOA histograms at 20-dB SNR are shown in Fig. 2 and Fig. 3, respectively. The results are shown in TABLE II. The corresponding accuracy plots are show in Fig. 4 and Fig. 5. The E_S and E_A results closely approximate the true value. The spread of signal three simulated the multipath effect. Signal two and signal three have some interference. One can see that the SD_A1s are close to their true values since the AOA histogram lobe of signal one is distinct. Note that in this simulation, the AOA SDs were set purposely to be independent of the SNRs. In practice, as the SNR

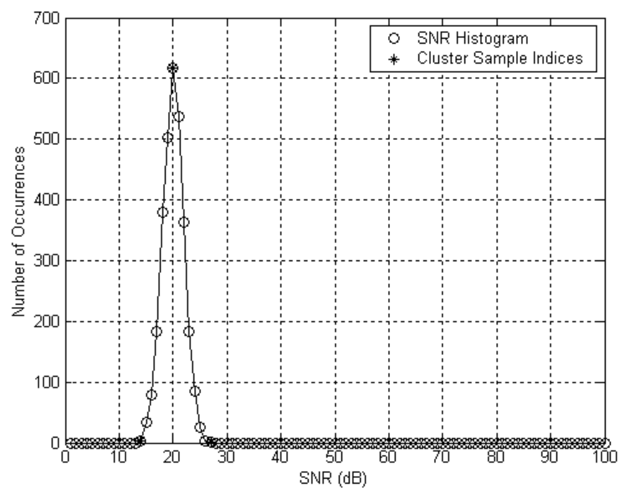

Fig. 2. Simulated Test SNR histogram at 20-dB SNR

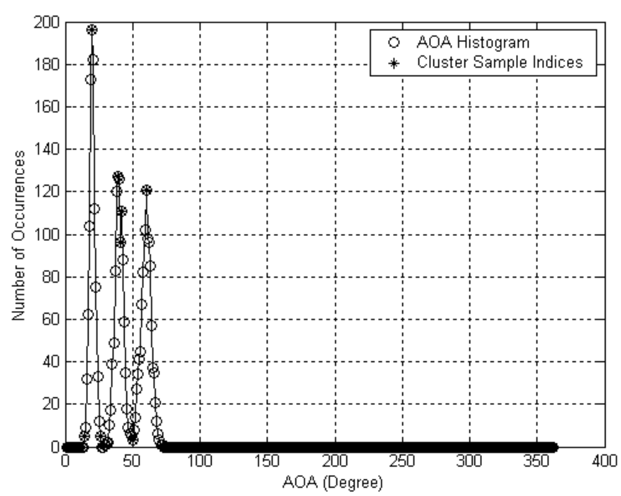

Fig. 3. Simulated Test AOA histogram at 20-dB SNR

increases, the AOA SD decreases, which will be shown in the results of the CRC-measured data later on. It is not a goal of this study to find a proper simulation model between the AOA SDs and the SNRs.

CRC Test18 Scenario: This corresponds to Location Scenario 6 (transmitter at (122° , 300 meters) beside a building) with a 905 MHz FM signal and a high receiver. The SNR and AOA histograms at 20-dB SNR

TABLE II. SIMULATED TEST RESULT

SNR	5	10	15	20	25	30	35	40
E_S	5.129	9.9943	14.96	19.957	24.9	29.9	35.0	39.814
E_A1	19.954	20.071	20.086	19.980	19.990	20.2	20.0	20.044
E_A2	39.777	39.790	40.337	39.957	40.205	40.4	39.9	40.028
E_A3	59.730	59.901	60.360	60.333	59.818	60.4	59.9	60.050
SD_A1	2.0001	2.0013	2.0001	2.0033	2.0032	2.00	2.00	2.0016
SD_A2	2.8839	2.8868	2.5853	2.5821	2.5823	3.16	2.58	2.8957
SD_A3	3.4577	2.9001	3.1633	3.1634	3.1938	3.16	3.16	2.8725

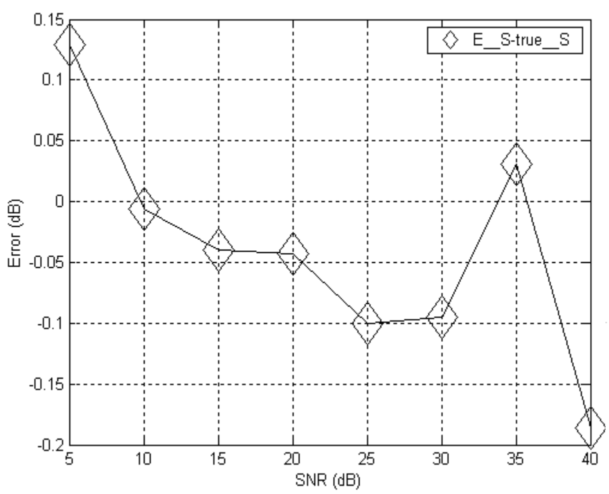

Fig. 4. Simulated Test SNR accuracy

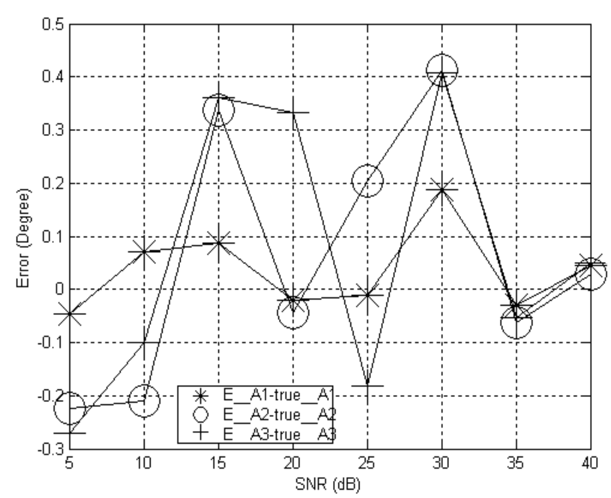

Fig. 5. Simulated Test AOA accuracy

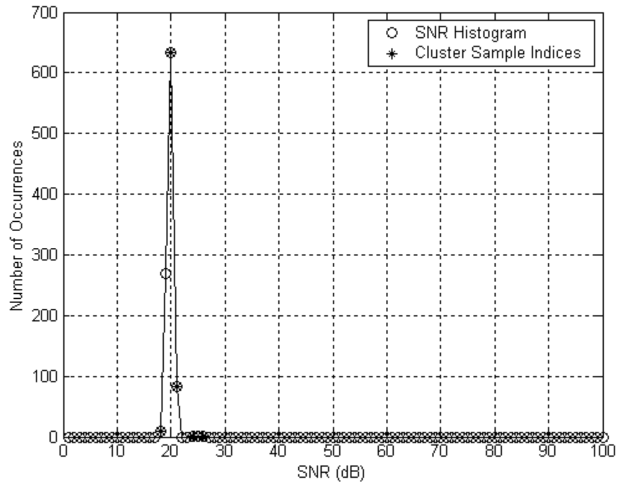

Fig. 6. CRC Test18 SNR histogram at 20-dB SNR

are shown in Fig. 6 and Fig. 7, respectively. The results are shown in TABLE III. The corresponding accuracy plots are shown in Fig. 8 and Fig. 9. Although a building is close to the transmitter in this case, the multipath effect is not very significant. One can see that there is only one AOA histogram lobe and AI_A ≈ SD_A for various SNRs, especially from 20 to 35 dB. Note that the AOA static error comes from inaccurate angle alignment between the transmitter and receiver.

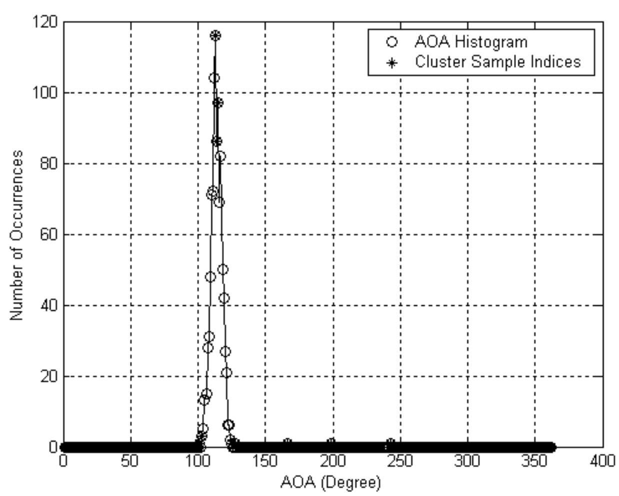

Fig. 7. CRC Test18 AOA histogram at 20-dB SNR

TABLE III. CRC TEST18 RESULT

SNR	5	10	15	20	25	30	35	40
E_S	5.7	10.5	15.0	19.8	27.4	32.0	36.7	40.8
E_A	113.58	114.73	115.59	113.57	117.89	117	116	109.87
AI_A	21.248	13.152	7.7716	4.5715	2.0420	1.21	0.74	0.1770
SD_A	26.664	11.326	6.9228	4.0318	2.0029	0.82	0.82	1.4204

CRC Test23 Scenario: This corresponds to Location Scenario 7 (receiver at (10°, 350 meters) behind 20' high trees) with a 39 MHz FM signal and a high receiver. The SNR and AOA histograms at 20-dB SNR are shown in Fig. 10 and Fig. 11, respectively. The results are shown in TABLE IV. The corresponding accuracy plots are shown in Fig. 12 and Fig. 13. In this case, some 20' trees block the receiver which is at high position (about 25 feet in height). With the low blocking trees in front of the high receiver, the multipath effect from the trees is not very significant, when the signal frequency is relatively low (39 MHz). The accuracy of SNR and AOA is better than the result in Test18. Again, AI_A ≈ SD_A for SNRs from 20 to 35 dB. The effect introduced by both buildings and trees is an appropriate topic for future study.

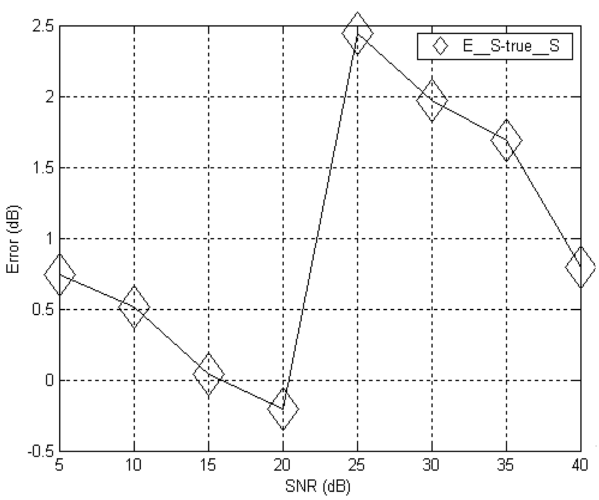

Fig. 8. CRC Test18 SNR accuracy

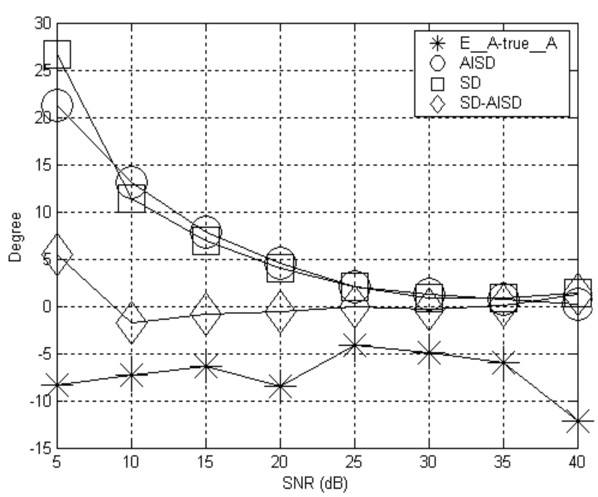

Fig. 9. CRC Test18 AOA accuracy

CRC Test17 Scenario: This corresponds to Location Scenario 6 (transmitter at (122°, 300 meters) beside a building) with a 905 MHz AM signal and a high receiver. The SNR and AOA histograms at 20-dB SNR are shown in Fig. 14 and Fig. 15, respectively. The results are shown in TABLE V. Although a building is close to the transmitter in this case, the multipath effect is not very significant. The corresponding accuracy plots are shown in Fig. 16, Fig. 17 and Fig. 18. There are two peaks in the SNR histogram due to the amplitude variation of the AM signal. Note that the AM type and its characteristics have to be identified by

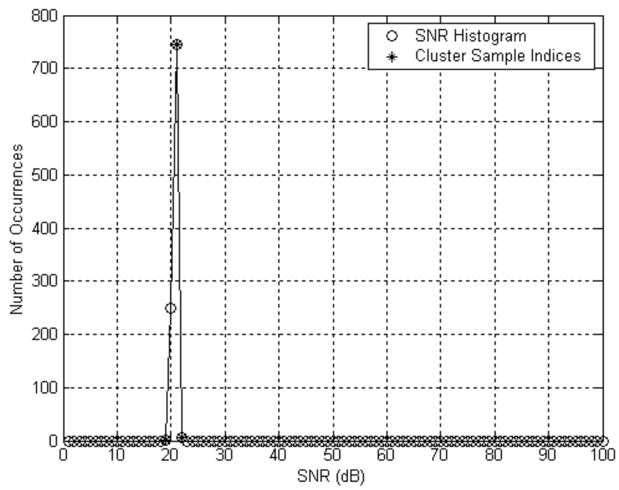

Fig. 10. CRC Test23 SNR histogram at 20-dB SNR

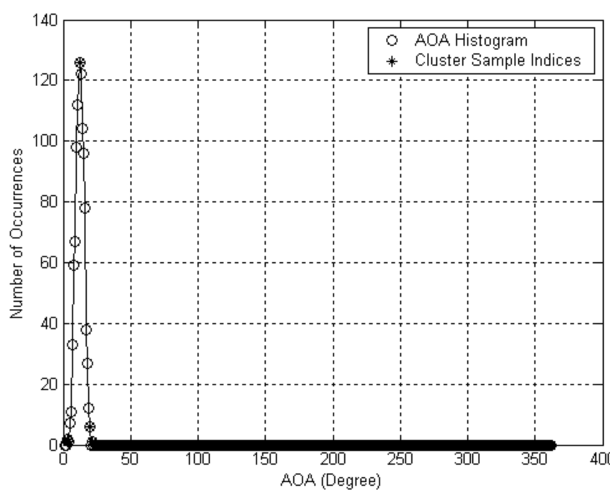

Fig. 11. CRC Test23 AOA histogram at 20-dB SNR

TABLE IV. CRC TEST23 RESULT

SNR	5	10	15	20	25	30	35	40
E_S	6.0043	11.095	15.504	20.756	25.936	30.8	35.9	41.237
E_A	4.5275	13.709	12.703	12.388	12.422	12.0	12.4	12.657
AI_A	20.759	11.531	6.9510	3.8350	2.1150	1.15	0.79	0.0750
SD_A	23.299	10.686	6.3475	3.4539	1.7096	0.82	0.52	0.5241

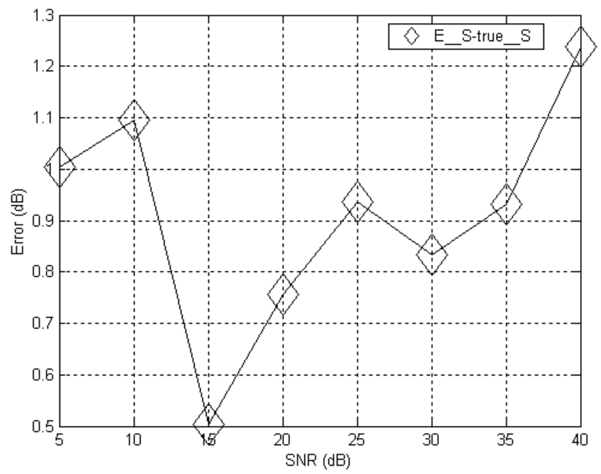

Fig. 12. CRC Test23 SNR accuracy

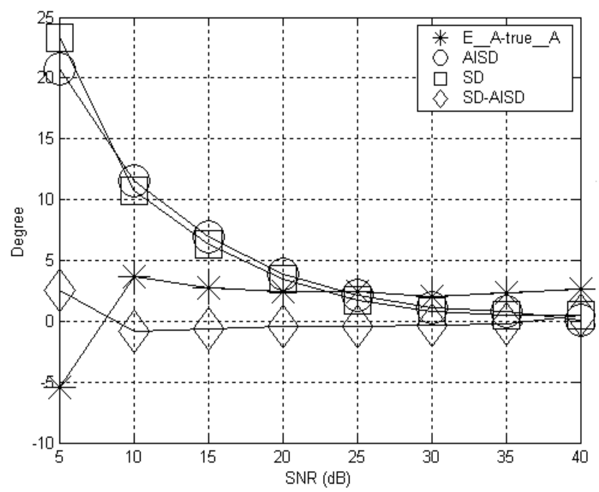

Fig. 13. CRC Test23 AOA accuracy

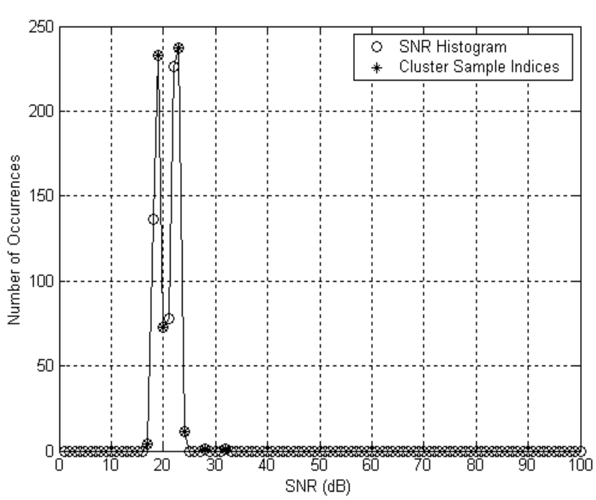

Fig. 14. CRC Test17 SNR histogram at 20-dB SNR

other algorithms ([1], [6] and [7]). Since 60% modulation index with 3.6 kHz bandwidth was used, and the time step between consecutive scans of the SE was not fixed (about 300 ms), the amplitudes of the scanned AM samples varied among scans. For the extreme case, the AM's maximum amplitude can be as large as four times (about 12 dB) its minimum. From Fig. 14, since the smallest valid SNR is 17 dB (the leftmost star in the main lobe) and the largest valid SNR is 23 dB (the rightmost star in the main lobe), the result is reasonable. The final results (E_Savg, E_Aavg) are the average of (E_S1, E_A1) and (E_S2, E_A2). The averaged SNR and AOA accuracy is close to the FM counterpart in Test18. Again, the AOA static error comes from inaccurate angle alignment between the transmitter and receiver. This AM effect is also a proper topic for future study.

Study of Limitation: Two signals (Signal_1 and Signal_2) were simulated with 1 to 5-dB SNR SDs and 1 to 5° AOA SDs. Signal_1 has 5 to 40-dB SNRs with 5-dB increment at 21° AOA. Signal_2 has 40-dB SNR at 20° AOA. Since the AOA SDs of both signals vary, it simulates the various AOA fluctuations between

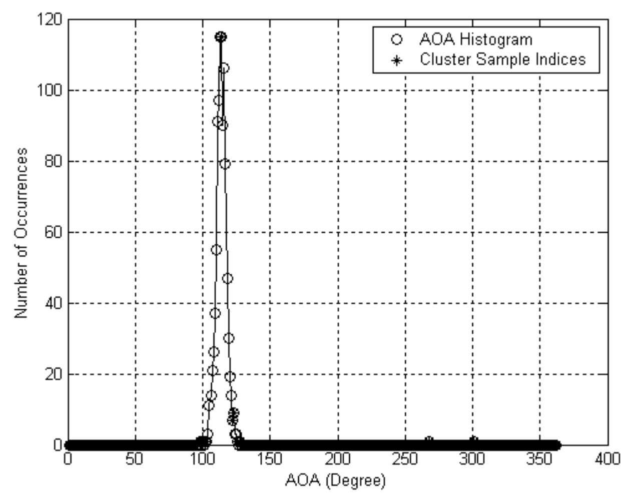

Fig. 15. CRC Test17 AOA histogram at 20-dB SNR

TABLE V. CRC TEST17 RESULT

SNR	5	10	15	20	25	30	35
E_S1	7.0068	9.4573	14.349	18.841	23.754	29.224	33.384
E_S2	-	12.476	17.585	22.056	27.042	32.513	36.690
E_A1	114.96	112.75	113.55	113.58	114.81	114.19	111.54
E_A2	-	114.78	112.95	113.81	115.10	114.32	111.42
AI_A1	19.368	14.653	8.4600	5.0516	2.6765	1.4971	0.9963
AI_A2	-	10.676	5.9791	3.3824	1.8153	1.0352	0.7481
SD_A1	21.162	15.924	7.8082	4.9334	2.0090	1.4271	1.1189
SD_A2	-	10.466	4.8993	3.1677	2.0024	1.1326	1.1211
E_Savg	-	10.967	15.967	20.449	25.398	30.869	35.037
E_Aavg	-	113.77	113.25	113.70	114.96	114.26	111.48

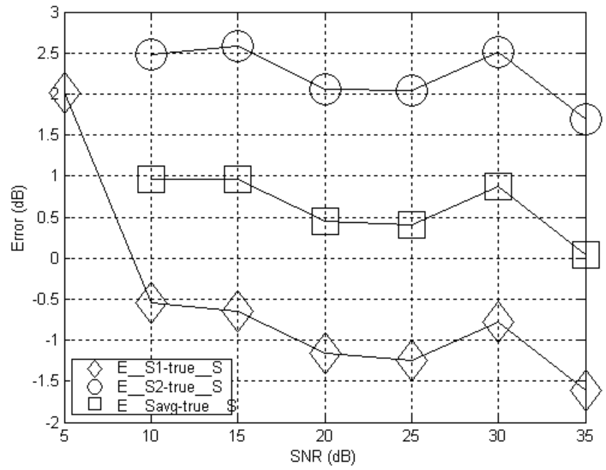

Fig. 16. CRC Test17 SNR accuracy

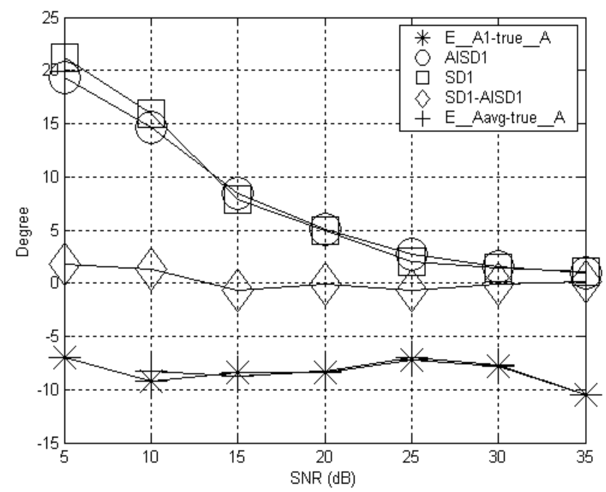

Fig. 17. CRC Test17 AOA accuracy - part 1

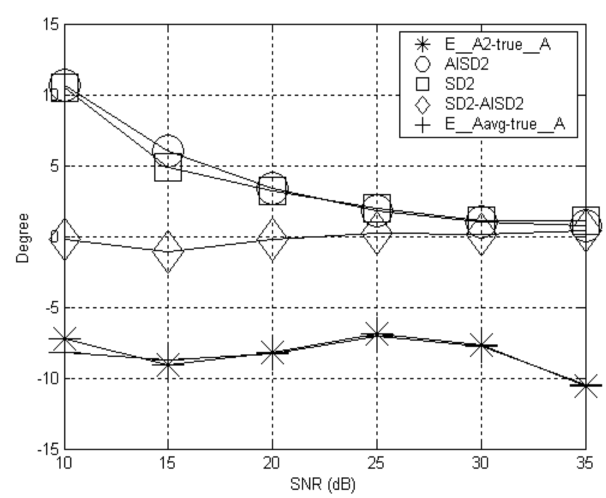

Fig. 18. CRC Test17 AOA accuracy - part 2

two close signals in the aspect domain. Also, although Signal_2 has fixed SNR, the SNR of Signal_1 (SNR1) and the SNR SDs of both signals vary, which simulates the various SNR fluctuations between two signals. Like the Simulated Test Scenario, the AOA SDs were set purposely to be independent of the SNRs. For scenarios with *I*-dB SNR SD and I° AOA SD, the corresponding E_S*I* and E_A*I* for both signals are obtained. The estimated results of Signal_1 and Signal_2 for 1000 scans are shown in TABLE VI and TABLE VII, respectively. From both tables, the smaller AOA and SNR SDs and the bigger SNR of Signal_1 are, the more accurate the E_S and E_A become. However, as the SNR1 increases to 40 (35 in one case) dB, both signals tend to be merged. Also, the estimations fail when AOA and SNR SDs are big (4, 5-deg/dB in this study) and SNR1 is low (5, 10-dB in this study). In general, when the AOA and SNR SDs are not significant, the histogram-based algorithms can estimate close signals with great accuracy. The estimations of Signal_1 and Signal_2 for 25 scans are shown in TABLE VIII and TABLE IX, respectively. From both tables, one can see that the estimations are not as accurate as the 1000-scan cases. However, again, when the AOA and SNR SDs are not significant, the histogram-based algorithms can estimate close signals with great accuracy, even when the number of scans is low.

TABLE VI. RESULT FOR SIGNAL_1 (1000 SCANS)

SNR1	5	10	15	20	25	30	35	40
E_S1	5.5007	9.958	14.958	19.958	24.958	30.0	35.1	39.990
E_A1	21.002	21.020	21.020	21.020	21.020	21.0	21.0	-
E_S2	4.9085	9.921	14.921	19.921	24.921	30.0	34.7	39.968
E_A2	21.076	21.071	21.071	21.071	21.071	21.1	21.0	-
E_S3	5.8986	9.9716	14.876	19.876	24.814	30.3	37.3	39.723
E_A3	21.005	21.117	21.117	21.117	21.118	21.1	-	-
E_S4	-	9.5632	14.750	19.720	25.041	29.7	34.3	39.237
E_A4	-	21.157	21.152	21.139	21.11	21.1	21.0	-
E_S5	-	-	17.137	22.397	25.539	30.1	35.2	38.677
E_A5	-	-	21.021	21.017	20.115	21.2	20.1	-

TABLE VII. RESULT FOR SIGNAL_2 (1000 SCANS)

SNR1	5	10	15	20	25	30	35	40
E_S1	40.021	40.021	40.021	40.021	40.021	40.0	40.0	39.990
E_A1	20.007	20.007	20.007	20.007	20.007	20.0	20.0	-
E_S2	40.031	40.031	40.031	40.031	40.031	40.0	39.8	39.968
E_A2	20.014	20.014	20.014	20.014	20.014	20.0	20.1	-
E_S3	38.644	38.644	38.644	38.644	38.619	40.1	37.3	39.723
E_A3	19.941	19.941	19.941	19.941	19.942	19.9	-	-
E_S4	-	38.302	38.302	38.554	38.548	38.6	40.6	39.237
E_A4	-	20.139	20.139	20.130	20.111	20.2	20.1	-
E_S5	-	37.878	37.878	37.853	37.580	40.9	40.2	38.677
E_A5	-	20.034	20.034	20.034	19.947	19.8	20.2	-

TABLE VIII. RESULT FOR SIGNAL_1 (25 SCANS)

SNR1	5	10	15	20	25	30	35	40
E_S1	5.08	10.08	15.08	20.08	25.08	30.1	35.1	40.04
E_A1	21	21	21	21	21	21	21	-
E_S2	5.2	10.2	15.2	20.2	25.2	30.2	34.9	40.16
E_A2	20.960	20.960	20.960	20.960	20.960	21.0	21.1	22.191
E_S3	5.6	9.5714	14.571	19.571	24.571	29.6	-	41.167
E_A3	21.268	-	-	-	-	-	-	23.385

TABLE IX. RESULT FOR SIGNAL_2 (25 SCANS)

SNR1	5	10	15	20	25	30	35	40
E_S1	40	40	40	40	40	40	40	40.04
E_A1	19.75	19.75	19.75	19.75	19.75	19.8	19.8	-
E_S2	40.12	40.12	40.12	40.12	40.12	40.1	39.7	40.16
E_A2	19.240	19.240	19.240	19.240	19.240	19.2	19.4	19.088
E_S3	41.533	41.533	41.533	41.533	41.533	41.5	41.5	41.167
E_A3	-	-	-	-	-	-	-	18.120

V. Conclusions

The purpose of this study is to determine the wireless channel usage or the station occupancy of fixed frequency channels using a wideband scanning device.

The results of this study show the effectiveness of using the histogram-based algorithms to analyze and estimate the channel usage using a significantly small number of scanned samples. Both simulated and measured data sets were processed and their results show significant accuracy for various scenarios, including the LOS and multipath FM signal cases. However, the results of the LOS AM signal cases show multiple peaks in the SNR histograms due to the amplitude variation of the AM signals. Thus, the histogram-based algorithms in this study solely cannot be used to classify the channel usage of the LOS AM cases. The AM type and its characteristics have to be identified first by other algorithms. Then the averaged AM results from the histogram-based algorithms can be used as estimates for classification. As per the multipath AM cases, the histogram-based algorithms may not be able to do the classification correctly.

In general, the histogram-based algorithms provide a simple and efficient way to classify the LOS channel usage correctly. Further study of the multipath effect and signal types other than AM and FM should be done in the future to test the robustness of the algorithms.

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