Appeared in the Proceedings of the First International Workshop on Technology and Policy for Accessing Spectrum (TAPAS2006).

Wideband Spectrum Probe for Distributed Measurements in Cellular Band

Nilay Shah, Theodoros Kamakaris, Uf Tureli
Wireless Network Security Center
Stevens Institute of Technology
Email: nshah9,tkamakar,utureli@stevens.edu
Milind Buddhikot
Lucent Bell Laboratories
Email: mbuddhikot@lucent.com

***Abstract*— One of the foremost critical design problems in cognitive radios is the need to process wide bandwidth and reliably detect the presence of primary users. This places significant requirements on sensitivity, dynamic range and linearity of the RF front-end. In order to counter effects of different adverse scenario of sensing channel it is necessary to perform distributed measurements to detect the primary user with high reliability. This paper presents the architecture of a sensing probe for wideband measurement and distributed measurement method to measure, characterize and model the utilization of the spectrum. Here, we have presented the sample spectrum measurement result using described sensing probe in cellular band.**

I. Introduction

It is common belief that there is a spectrum scarcity at frequencies that can be effectively used for wireless communications. This concern has arisen from the intense competition for use of spectra at frequencies below 3 GHz. The Federal Communications Commissions (FCC) frequency allocation chart indicates overlapping allocations over all of the frequency bands, which reinforces the scarcity mindset. On the other hand, actual measurements taken in downtown Berkeley are believed to be typical and indicate low utilization, especially in the 3-6 GHz bands. In [1],[2] the power spectral density (PSD) of the received 6 GHz wide signal collected for a span of 50 second sampled at 20 MS/s. This view is supported by recent studies of the FCC Spectrum Policy Task Force who reported [3] vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15 to 85 percentage. In order to utilize these spectrum white spaces, the FCC has issued a notice of proposed rule making (NPRM [4]) advancing cognitive radio (CR) technology as a candidate to implement negotiated or opportunistic spectrum sharing.

Wireless systems today are governed by wasteful static spectrum allocations, fixed radio functions, and limited network coordination. Some systems in the unlicensed frequency bands have achieved increased spectrum efficiency, but are faced with increasing interference that limits network capacity and scalability. Cognitive radio systems offer the opportunity to use dynamic spectrum management techniques to help prevent interference, adapt to immediate local spectrum availability by creating time and location dependent in virtual unlicensed bands, i.e. bands that are shared with primary users. Unique to cognitive radio operation is the requirement that the radio is able to sense the spectrum over vast bandwidths and adapt to it since the radio does not have primary rights to any pre-assigned frequencies. In [5] was shown that collaborative techniques gives improved performance in primary user detection.

The paper is organized as follows; Section II describes the wideband spectrum sensing probe for measurements in Cellular band and Section III presents its limitations. Section IV discusses the distributed measurement architecture. In section V we present measurements obtained with our wideband spectrum sensing probe and analysis of those results in terms of Spectrum Utilization. Finally, conclusions are presented in Section VI.

II. Spectrum Probe Architecture.

The wideband Sensor probe developed consists of three distinct modules as shown in Figure 1: a wideband RF receiver that downconverts from RF to baseband and digitizes to 10 bit I/Q data at 40 Msamples per second; a high speed data acquisition module with 256 MB of RAM, capable of storing 2.5 seconds of contiguous signal and; a local area network (LAN) module that allows control and data communications with the entire asembly, so that the probe can be placed anywhere within a LAN or potentially wireless LAN (WLAN) for remote data collection.

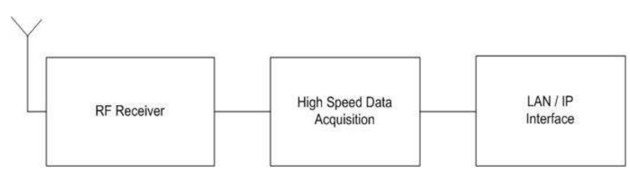

Fig. 1. Sensing Probe Architecture

A. RF RECEIVER

The front end of the sensor probe consists of a RF receiver (shown in Figure 2) tunable to frequency range 800 MHz - 1000 MHz. RF receiver sensitivity is -56 dBm for a full scale RF input and includes dual 10 bit Analog-to-Digital converter. This module has built in automatic gain control (AGC) with 70 dB dynamic range. It can be tuned to entire range of frequency with the step size 100, 31.25 or 25 KHz. The modularity of the system allows for the frontend to be easily exchanged with modules operating at other RF bands. The probe can be easily adapted for measurements in the PCS, LMRS or ISM bands.

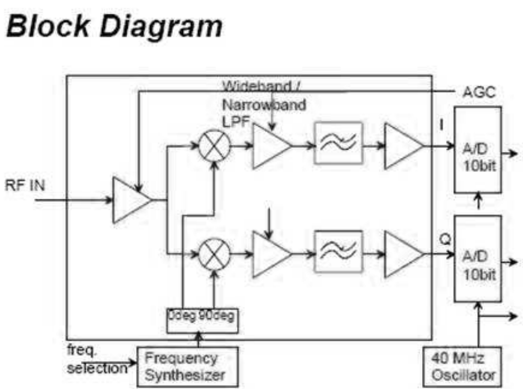

Fig. 2. RF Receiver Block Diagram

B. HIGH SPEED DATA ACQUISITION

The data acquisition module operates in half duplex record and then read mode. The captured signal is stored as received from the RF frontend and then read by the LAN/IP interface. This asynchronous operation is a limitation to the system, however allows for enough contiguous data to be received for most purposes of analysis. Given the ADC characteristics, 2.56 seconds of contiguous signal can be captured. However transferring the data over the LAN is fairely bandwidth consuming, especially as the system scales to multiple probes. This necessitates a low duty cycle of measurement vs. analysis which leads to a statistical sampling system. A second generation of this spectrum probe currently under development introduces an field programmable gate array (FPGA) module between the RF frontend and the data acquisition modules which will allow for preprocessing and compression of data.

C. LAN/IP NETWORK INTERFACE

Data collected at the data aquisition module are transferred for analysis to the data fusion center over the IP network via the LAN/IP network module. This module processes the data into IP packets and handles communications and control of all modules of the sensor probe through straight forward socket programming. The application programming interface (API) allows monitoring and control of sensor probe's modules using graphical user interface developed and running at the fusion center. Our sensor probe has TCP/IP interface versatile to support multiple data streams, with a standard TCP-IP socket for each stream. Also it has HDLC multiplexing of two tranmit streams consisting of transmit data channel and signaling channel. Similarly it support HDLC multiplexing of receiver data channel and signaling channel.

The modules described above are commercially off-the-shelf assemblies, available by Mobile Satelite Services Inc, programmed with essential communication and processing functions, including modulation, demodulation, error correction encoding and decoding, digital to analog/RF, RF/analog to digital, formatting, data storage and baseband interface. There are numerous types of ComBlock modules available, but for our spectrum sensing purpose we have a customized assembly consisting of comblock modules LAN IP interface module (Com-5001), Data acquisition module (Com-8002) and Front end receiver in cellular band (Com-3005) as show in Figure 1. More information is available at [6]

III. PROBE LIMITATIONS

As aforementioned the motivating application for the spectrum probe is that of cognitive radios and dynamic spectrum access(DSA). In general, cognitive radio sensitivity is assumed to outperform primary user receiver by a large margin in order to prevent what is essentially a hidden terminal problem. At the same time most developed DSA techniques envision wide band transmission that circumvent legacy users who are typically considered as narrow band interference. The problem becomes prohibitively challenging when requiring a receiver to achieve $30 - 40$ dB better sensitivity than one with two orders of magnitude lower bandwidth. Furthermore, the bandwidth of operation can potentially span through multiple legacy systems, with different transmission power levels and access characteristics. Even in the case of a single system such as the cellular band measured the characteristics of the uplink and the downlink bands effectively forced the experiments to be isolated within the downlink band, as the limited dynamic range of the wide band receivers did not allow the detection of the mobile transceivers in the presence of the significantly stronger basestation signals. Other receiver impairments that limited the fidelity of the system included a frequency offset up to 125 ppm, IQ isolation limited to 20 dB as well as the lack of a baseband filter sharp enough to protect from aliasing artifacts in the presence of strong out of band signals.

The limitations described are typical of receiver architectures, and especially characteristic of the wide band commodity hardware cost effectively utilized in the ISM bands. These limitations can be effectively addressed in the communication system design algorithmically however they impose fidelity bounds in the spectrum probe application and cumulatively increase the perceived measurement noise.

Another factor that must be assessed with the results is when the spectrum sensor probe is shadowed, in severe multipath fading, or inside buildings with high penetration loss while in a close neighborhood there is a primary user who is at the marginal reception. In these cases there is an increased probability of failing to detect the presence of primary user. In recent years, a number of studies and experiments have shown that distributed systems offer enhanced reliability due to inherent redundancy and increased performance by exploring concurrency and data fusion techniques.

IV. Distributed Measurement Architecture

The objective of the distributed multisensor data fusion system is to provide an accurate detection of spectrum in use, so that the probability of missing is minimized i.e secondary users interference to primary user can be minimized. Multisensor systems have an inherent redundancy. Due to the availability of data from multiple sensors, system performance and reliability is improved. When one or more sensor fails to detect presence of primary user due to large fading or shadowing, the system can continue to operate at a reduced performance level(graceful degradation). Also, use of multiple sensor allows an increase in coverage, both spatial and temporal. They can observe region larger than observable by a single sensor. Sensors confirm each other's inferences, thereby increasing confidence in the final system inference.

Distributed measurement architecture for spectrum sensing can be generally described as distributed detection with decision level fusion in parallel configuration. In decision level fusion, each spectrum sensor makes decision about occupation of channel based on its own data .These decisions are then combined to yield the final inference. Though better results can be achieved with feature fusion and data fusion techniques but that requires more data to be transfered to fusion center and hence an increase in overhead. In the described experients we are trying to detect the occupancy of GSM channels in the cellular band using the described spectrum probe. The logical architecture is depicted in Figure 3.

There are multiple level of pre-processing that can be applied before the probes output is sent to the fusion center. Obvious modes of operation would be outputing a binary vector indicating channel activity identified per probe (shown as output B) in 3. Other possible probes could output A matrix containing the power spectral distribution as measured at each location. These data can be inteligently fused to counter frequency selective fading by optimaly weighing measurements of different parts of the spectrum from different probes. Future work will attept to quantify the benefits of each mode of operation in terms of data overhead produced vs probability of detection.

A. Decision Fusion

Each probe senses the spectrum and local processing determines the availability or occupancy of a particular channel/slot in GSM. These decisions are transmitted to a fusion center that

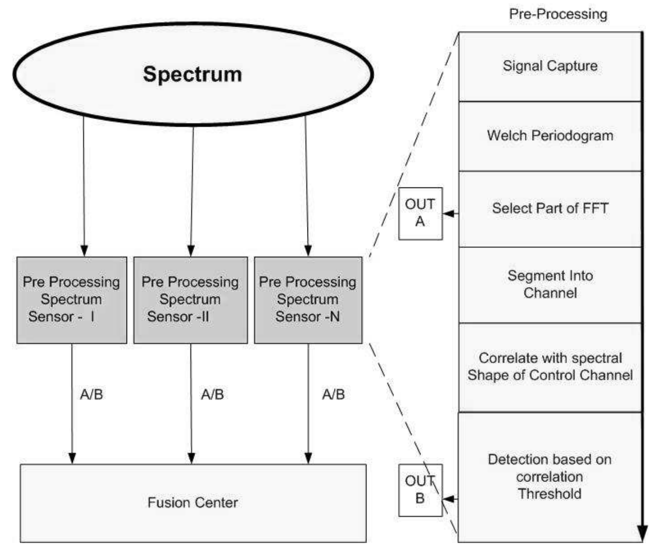

Fig. 3. Distributed Measurement Setup

combines them to yield the global inference, a data fusion method described in [7]. If the entired distributed detection system is considered, it is data in - decision out system, whereas the fusion center is a decision in - decision out system.

Fig. 4. Decision Fusion System

Following we present an overview of our fusion method for spectrum sensing. Consider a binary hypothesis testing problem with hypotheses H_0 and H_1 indicating the availability or non-avaibility of GSM channel respectively. Let P_0 and P_1 denote the prior probabilities associated with H_0 and H_1, respectively. There are N spectrum sensors that transmit their binary decision μ_i $i = 1, \ldots, N$, to the fusion center, where

$$\mu_i = \begin{cases} 0 & \text{if channel is available,} \\ 1 & \text{if channel is not available.} \end{cases} \tag{1}$$

this decision in decision out system shown in Figure 4,where the local spectrum sensor decisions are input and are combined to yield the output decision μ_0:

$$\mu_0 = \begin{cases} 0 & \text{if ouput decision is } H_0, \\ 1 & \text{otherwise.} \end{cases} \tag{2}$$

In this problem, a decision combining rule is a logical function with N binary input and one binary output for every channel. Commonly used fusion rules are OR, AND, MAJORITY etc. For application in spectrum sensing which requires higher accuracy "MAJORITY " can be used as fusion rule. It implies out of N spectrum sensor if more than $N/2$ inferences occupancy of channel, that channel is considered as in use and not available to primary user.

V. Measurement and Analysis

As described earlier Section (IV), we use off-the-shelf available comblock modules assembly as sensing probe capable of real time spectrum analysis.We use the off-the-shelf omni-directional antennas in cellular frequency range $800 - 1000$ MHz.

We determined the cellular bands used by various service provider through a frequency survey based on the FCC database and local measurements. In 5 illustrates the survey results for the Stevens Institute of Technology location in Hoboken, NJ for four providers, namely Verizon, Sprint, T-mobile and Cingular. As for time being we are concentrating on Cellular band and GSM only, results provided here are for Cingular network.

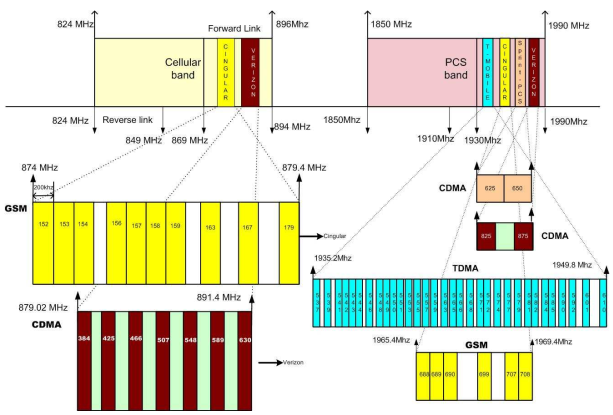

Fig. 5. Cellular/PCS Spectrum Survey in Hoboken, NJ

The GSM technology uses multiple 200 KHz carrier frequencies per cell (in uplink and downlink) and employs time division multiplexing(TDMA) to support concurrent user calls. The repeating slotted frame structure on each carrier contains 8 slots, each 577 microseconds, leading to a frame length of 4.615 ms. One straightforward measurement approach is to synchronize to each narrowband carrier, process TDM frames to detect slot occupancy and individually count number of timeslots active at a given sampling interval. However, given the presence of large number of carrier frequencies per cell and associated synchronization overhead, simple round robin monitoring leads to significant increase in the measurement time. Also, as described in Section (IV), our simple sensing probe has wideband sensing ability and that helps in minimizes the measurement times compare to round robin technique using sophisticated equipment like spectrum analyzer. One of the problem encountered during measurements involves the I-Q leakage from the sensing probe and to overcome it, we artifact our band of interest in the real side of PSD. An FFT-based spectral analysis is then used to make a statistical decision as to which channels and slots per channel in the band are active for the duration of the sampling interval. Sensing probe has capability of collecting the predetermined number of bytes in data and that allows the capture of one timeslot every second and therefore, higher the loading, higher is the probability of capturing an active timeslot for each channel. Threshold value is decided with few experimental results to determine the number of active channels and timeslots throughout those captures.

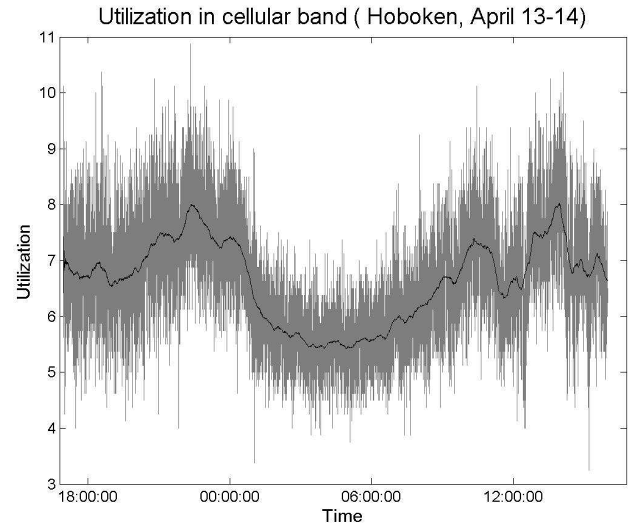

Fig. 6. First time slot occupancy for One day in Hoboken for Cingular.

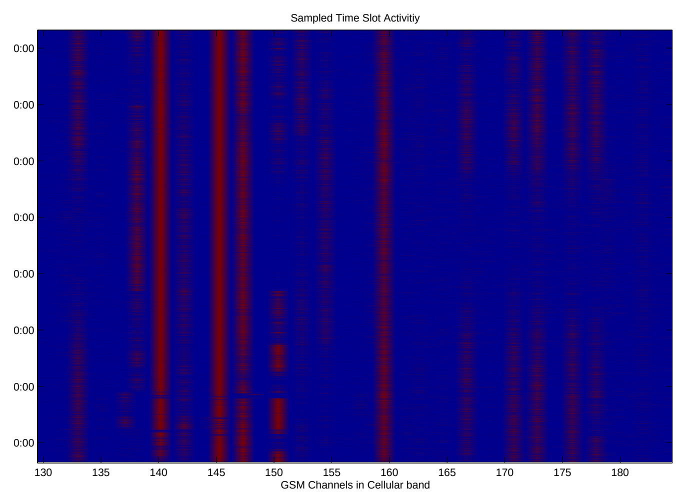

Fig. 7. First time slot occupancy for One day in Hoboken for Cingular.

Completion of a snapshot of reading, which involves data capturing equivalent to 4.615 ms, for GSM based provider in Cellular band and transfer of the data to laptop takes almost 6 seconds using one comblock. In case of distributed measurement with multiple comblock takes time equivalent to 6 seconds time to number of comblock. The entire setup is automated for continuous 24×7 measurement extending over a period of week or more, limited by storage available on laptop controlling the spectrum analyzer.

As shown in Figure 3, GSM channel utilization is measured through analysis of power spectral density of entire snapshot data for a allocated spectral band to provider. Signal processing techniques like Welch periodogram is used on captured data to determine GSM channels and their utilization. For GSM Networks, we define a "used channel" in terms of a timeslot occupied in one modulated carrier.

Analysis of power spectral density is done with the help of Welch periodograms of captured data over the entire band of frequencies corresponding to GSM carriers provides information regarding timeslot occupancy over time. we have divided captured data vector in to 8 segments, where each segment reflects the data captured equal to one particular timeslot. After applying Periodograms to this segmented data, we can just filter out PSD estimates of our frequency of interest as originally data captured by our Wideband sensing probe has frequency range of 20 MHZ. Figure 7 shows the first timeslot of every channel in cellular band frequency of Cingular.

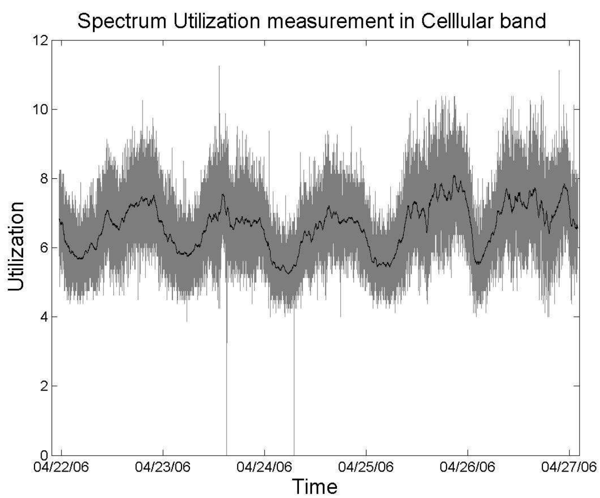

Fig. 8. Spectrum Utilization Measurement in Cellular band over 5 day period.

Similarly Figure 6 shows the utilization in entire cellular band for Cingular. Results in this measurement are very similar to results presented in [2]. In Figure 6 blue smooth curve is achieved after applying smoothing to original utilization show in grey. Figure 8 shows the utilization in cellular band for 5 days of data collected at Hoboken, NJ. Figure 9 shos the first time slot occupancy and Figure 10 represents the percentage utilization of GSM Channels in cellular band. From the above Figure we have the following observations.

A. Bimodal Behaviour

GSM utilization defined in terms of "Used Time Slot/Channel" exhibits bimodal behaviours. These results coincide with the result presented in [2] with same band

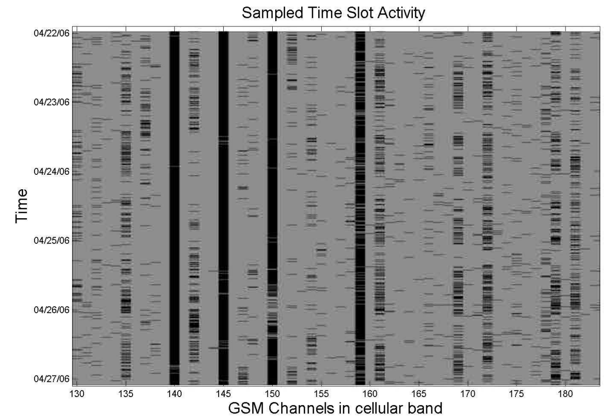

Fig. 9. First time slot occupancy for 5 days in Hoboken for Cingular.

measurement. Two peaks seen in the behaviour of spectrum utilization corresponds to timing in morning and evening.

B. Even Channel Usage

From Figure 10, which shows the channel usage for 5 days and we can see that channel usage is even between different channels which are active and that may be due to slow frequency hoping used for all active careers, as specified in GSM standard to migigate the effect of frequency selective fading.

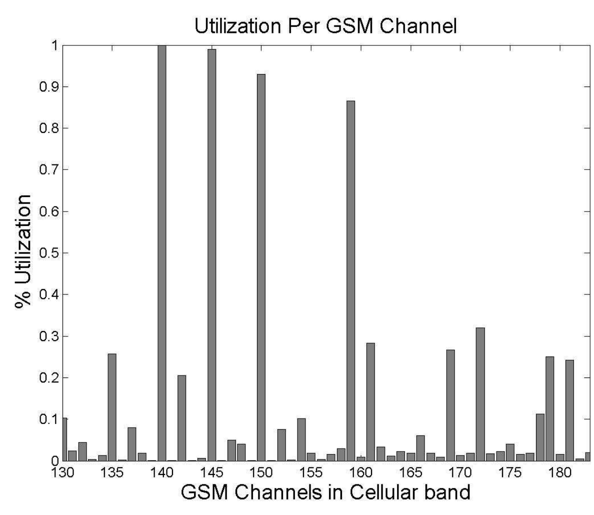

Fig. 10. Average Utilization of GSM Channel in Cellular band over 5 days.

VI. Conclusion

In the paper, we are presenting a wideband spectrum probe developed for spectrum occupancy measurements in the Cellular bands. Special emphasis has been awarded to the limitations of such receiver based spectrum probe in terms of confidence in measurement accuracy for primary user detection. We envision low cost commodity hardware to be used for purposes of spectrum sensing and environment awareness for cognitive radios and we attempt to identify experimentally the significance of receiver impairments towards this goal. Furthermore we advocate density in lieu of fidelity for such receivers and propose a distributed measurement architecture to mitigate these limitations as well as the problems that arise due to adverse channel conditions. Finally we present collected measurements utilizing these probes in the cellular band, as well as analysis of those measurements in terms of network loading over time.

Acknowledgment

This work is funded by National Science Foundation (NSF) grant CNS-0435348.

References

[1] J. Yang, "Spatial channel charectrization for cognitive radios," *UC Berkeley*, 2004.
[2] T. Kamakaris, M. Buddhikot, and R. Iyer, "A case for coordinated dynamic spectrum access in cellular networks," *Proceedings of the First IEEE International Symposium on New Directions in Dynamic Spectrum Access Networks*, Nov 2005.
[3] FCC, "Spectrum policy task force report," *ET Docket No.02-155*, Nov 2002.
[4] ——, "Et docket no 03-322," *Notice of Proposed Rule Making and Order*, Dec 2003.
[5] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," *Proceedings of the First IEEE International Symposium on New Directions in Dynamic Spectrum Access Networks*, Nov 2005.
[6] "Communication block inc." [Online]. Available: www.comblock.com
[7] P. K. Varshney, "Multisensor data fusion," *Electronics and Communication Engineering Journal*, vol. 9, no. 6, pp. 245–253, Dec 1997.