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NATIONAL TAIWAN UNIVERSITY
TAIPEI, TAIWAN, R.O.C

I, Lin-shan Lee, Ph.D., declare and state as follows:

1. I am a professor at the National Taiwan University in Taipei, Taiwan in the Department of Electrical Engineering.

2. Neither I nor National Taiwan University is being compensated for this declaration.

3. In 2009, I was the General Chair of the Institute of Electrical and Electronics Engineers, Inc. ("IEEE") International Conference on Acoustics, Speech, and Signal Processing ("2009 ICASSP"). As General Chair of the 2009 ICASSP, my duties included overseeing the organization of the conference, selection of programs during the conference, and publication of the proceedings, among other duties.

4. The 2009 ICASSP was held on April 19-24, 2009 in Taipei, Taiwan. I attended the conference in my duties as General Chair. Attendants of the conference included people in industry, professors, and others interested in audio signal processing. There were approximately 1600 people that attended the 2009 ICASSP.

5. As part of the conference, there was a call for papers from the industry. In my duties as General Chair, I organized the collection, selection, and publication of the conference proceedings. These conference proceedings were compiled and published in the IEEE International Conference on Acoustics, Speech, and Signal Processing Proceedings ("Conference Proceedings"). The Conference Proceedings were distributed to attendants on the first day of the conference on April 19, 2009.

6. The Conference Proceedings included an article by Qi (Peter) Li, Manli Zhu, and Wei Li entitled "A Portable USB-Based Microphone Array Device for Robust Speech Recognition." A copy of this article is attached to my declaration as Exhibit A.

I declare, under penalty of perjury, that all statements herein made of my personal knowledge are true and that all statements made on information and belief are believed to be true. Also, all statements made herein were made with the knowledge that willful false statements and the like are punishable by fine or imprisonment or both under Section 1001 of Title 18 of the United States Code.

Dated: April 20, 2020

Lin-Shan Lee, Ph.D.

EXHIBIT A

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April 19-24, 2009

IEEE International Conference on Acoustics, Speech, and Signal Processing Proceedings

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Tianhao Zhang, University of Pennsylvania
Tong Zhang, Rensselaer Polytechnic Institute
Xinmiao Zhang, Case Western Reserve University
Yimin Zhang, Villanova University
Zhang Zhang, National Laboratory of Pattern Recognition (NLPR) Institute of Automation, Chinese Academy of Sciences (CASIA)
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Qing Zhao, University of California at Davis
Yunxin Zhao, University of Missouri
Jing Zheng, SRI International
Thomas Zheng, Tsinghua University
G. Tong Zhou, Georgia Institute of Technology
Huiyu Zhou, Brunel University
Shengli Zhou, University of Connecticut
Xiang Zhou, City University of New York
Yue Zhou, Microsoft Corporation
Xingquan (Hill) Zhu, Florida Atlantic University
Imed Zitouni, IBM TJ Watson Research Center
Athanasia Zlatintsi, National Technical University of Athens
Udo Zoelzer, Helmut-Schmidt-University Hamburg
Abdelhak Zoubir, Darmstadt University of Technology
Geoffrey Zweig, Microsoft

General Chair's Welcome Message

On behalf of the organizing committee of ICASSP 2009 and the IEEE Signal Processing Society, I am delighted to welcome you to join us at the 34th IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), which will be held at the Taipei International Convention Center in Taipei, Taiwan, April 19-24, 2009. The ICASSP meeting is the world's largest and most comprehensive technical conference focused on signal processing and its applications. The conference will feature world-class speakers, exhibits, and over 140 lecture and poster sessions.

It is apparent that the frontiers of science as well as various new technologies have created a completely new horizon of signal processing. The ICASSP 2009 theme is hence "Signals over the Horizon." It is our hope that signals about such frontiers and new technologies and beyond will be transmitted from the conference and received all over the world.

This will be the second ICASSP held physically in Asia after the first one, ICASSP 1986 in Tokyo. ICASSP 2003 was originally to be held in Hong Kong, but was unfortunately canceled due to the SARS scare, resulting instead in a virtual conference. We are pleased that ICASSP is coming back physically to the region after 23 years, and treasure this extraordinary opportunity to host ICASSP 2009 in Taipei. This will no doubt be one of the most notable national events in Taiwan for years. We would like to take this opportunity to invite you to experience the modern, oriental metropolis of Taipei with Taiwanese-style hospitality. We are sure you will find this conference to be an excellent forum for innovative and technical discussions, and a natural environment for extending friendship and fellowship.

The Asia-Pacific region has emerged as a significant force driving the future in terms of technology development and innovations, global market and economics, as well as culture development. The world has witnessed the evolution of this region over the past few decades. It is an area full of diversity and excitement, and Taiwan is the pivotal location of this region.

Formerly called "Formosa"—the "beautiful island"—by the Europeans, the island of Taiwan is located in the Pacific Ocean off the southeast coast of China, from which it is separated by the Taiwan Strait. Taiwan has a dense population of over 23 million people, and is endowed with a wide variety of breathtaking natural scenery, from the sublime marble cliffs of Taroko Gorge to the coral reefs and beaches of Kenting. Taiwan is full of beautiful mountains, with more than 100 peaks above 3,000 meters. Classical Chinese culture is faithfully preserved in Taiwan, and traditional Chinese flavor flourishes everywhere. Historically, Taiwan has always been a melting pot of cultures, including those of Europe, Japan, and America, and the influences of these cultures have naturally fused with the island's aboriginal cultures.

The people of Taiwan have made it a national goal to construct a green silicon island, promoting the development of information and electronics technologies as well as industry, while preserving the island's beautiful natural resources. Established as an IT industry stronghold since the 90's, Taiwan ranked among the world's top 4 suppliers of information products in 2002. Today, Taiwan hosts the world's largest suppliers of notebook PCs, motherboards, and liquid crystal display (LCD) monitors. Taiwan's eight major IT products also include desktop PCs, servers, digital still cameras (DSCs), optical disk drives, and color display tube (CDT) monitors. More than 83% of Taiwan's households have computers. Internet users number about 75% of the island's population, while the mobile phone penetration rate reaches over 99%.

Taipei, located in northern Taiwan, covers 270 square kilometers, with a population of 2.6 million people. It is the largest city in Taiwan. In addition to the friendly, hospitable nature of its inhabitants, the rich cultural heritage and the high level of development have made Taipei a cosmopolitan city that brings together the traditional and the new. The National Palace Museum houses the world's finest collection of Chinese arts and crafts, and Taipei's beautiful temples are the setting for colorful folk festivals. The city is also the Chinese cuisine capital of the world. Visitors can enjoy the best of regional specialties from all parts of China; they may try a different cuisine for each meal during their stay in Taipei, and find each meal unforgettably exquisite. Taipei also boasts bustling night markets, areas of spectacular natural beauty, streets lined with shops selling brand-name products, and numerous international hotels. Taipei can meet all of the needs of people coming from all parts of the world, whether food, accommodations, entertainment, or meeting environments.

The conventional Technical Program of ICASSP 2009 has been ably coordinated by our Technical Program co-chairs, Professors Liang-Gee Chen of National Taiwan University and James R. Glass of MIT. Paper review was handled by the 13 Technical Committees of the IEEE Signal Processing Society with a rigorous review process. A total of 144 lecture and poster sessions was organized. Two additional Show & Tell sessions including demos featuring latest results of signal processing systems were also organized.

The program also includes a very strong tutorial program of 17 tutorials covering a wide range of balanced topics selected by a committee chaired by our Tutorial chair, Professor Tsuhan Chen of Carnegie Mellon University. The tutorial topics are:

1. Fundamentals
   - Beyond Bandlimited Sampling: Nonideal Sampling, Smoothness and Sparsity
   - Distributed Adaptive Filters and Networks
   - Signal and System Theoretic Foundations of Quantization and Data Acquisition (A/D and D/A conversion)
   - Sparse Sampling: Theory, Algorithms and Applications
2. Speech and Audio
   - Automatic Recognition of Natural Speech
   - Applications of Psychoacoustics to Signal Processing
   - Special Interests in Mandarin Speech Recognition and Chinese-to-English Machine Translation
3. Image and Video
   - Distributed Video Coding for Low Cost Multimedia Communications Systems
   - Distributed Processing in Smart Cameras
   - Digital Video Image Quality and Perceptual Coding
4. Communications
   - Distributed Source Coding: Theory, Code Designs and Applications
   - Peak-to-Average Power Ratio Reduction: Applications and Algorithms
   - A Unified Design Framework for Non-Linear MIMO Transceivers Using Majorization Theory
   - Game Theory and Resource Allocation in Wireless Communications
5. Retrieval
   - Analysis and Retrieval Techniques for Music and Motion Data
   - Recent Developments in Content-based and Concept-based Image/Video Retrieval
6. Implementation
   - Multimedia Signal Processing on CPU and GPU

with Many Cores

The program further includes a total of 12 special sessions and 4 panels selected by a committee chaired by our Special Session chair and co-chair, Professors Shih-Fu Chang of Columbia University and Lee Swindlehurst of University of California, Irvine. The 12 special sessions cover a wide range of topics:

- Multimedia Surveillance
- Voice Transformation
- Signal Processing Challenges for 4G Wireless Communications
- Distributed Signal Processing and Consensus Gossiping
- Handling Reverberant Speech: Methodologies and Applications
- Interference Channels and Spectrum Sharing
- Signal Processing for Neural Spike Trains
- Multimedia Social Networks
- Signal Processing Techniques and Algorithms on Robot Audition
- Signal Processing for Improper and Noncircular Complex-Valued Data
- The Data Deluge: the Challenges and Opportunities of Unlimited Data in Signal Processing
- Video Search and Event Analysis

The 4 very exciting panels are:

- LTE and WiMAX - What is Next? Challenges for 4G Wireless
- The Changing World of "Educational Resources" in Signal Processing Education
- Signal Processing for Human/Human and Human/Computer Communication
- Mobile Media Search: Has media search finally found it's perfect platform?

We have invited four distinguished plenary speakers, respectively from the U.S., Japan, Europe and Taiwan, presenting their views on topics ranging from academia to industry:

(1) Dynamic Spectrum Management
by John M. Cioffi, Stanford University & ASSIA Inc.

(2) Signal Processing Bringing on Market Growth – Its Industrial Successes and Future Expectations
by Kazuo Murano, President, Fujitsu Laboratories Limited

(3) Cognitive User Interfaces: an Engineering Approach
by Steve Young, University of Cambridge

(4) The Evolution and Trends of the Semiconductor Industry and Signal Processing SoC
by Ming-Kai Tsai, Chairman of the Board and Chief Executive Officer, MediaTek Inc.

In addition, we are experimenting an initiative by creating a new embedded program component, called Thematic Symposium (TS), in order to cultivate more coherent technical activities, achieving more educational goal, and enhance interdisciplinary interaction at ICASSP. A Thematic Symposium (TS) is a grouping of multiple technical sessions (including regular lecture/poster sessions, special sessions, panels, tutorials, and keynote talks) that share a common technical theme. Related activities of a TS are carefully scheduled in a streamline fashion over 1 or 2 days so that a continuous momentum is established without interruption or schedule conflict. To make the technical subjects of a TS more accessible to general audience, a new session exclusively dedicated to overview talks are also added to each TS, referred to as an overview talk session. Such overview talks are given by experts of the field and experienced speakers, with a specific objective to introduce emerging knowledge from the TS area to broader audience so that cross-disciplinary collaboration can be fertilized. Every overview talk is synchronized with two regular lecture presentations. Therefore, the goal of TS is two-fold: (1) adding multiple coherent threads to the overall program and (2) bridging the




discipline gaps by introducing the new overview talk sessions. With the strong support from the 13 technical committees and their volunteers, four outstanding TSs have been organized：

· **Signal Processing for 4G Wireless**
· **Network Distributed Signal Processing**
· **Immersive Communication**
· **Multimedia Search and Retrieval**

In addition, we made a special arrangement of video recording the presentations of plenary talks, special sessions and overview talks, upon the consent of the speakers and authors. These will be made available for online access by conference attendants within three weeks of the conference. In this way we hope people may be able to listen to talks they have to miss during the conference sessions, and listen to some talks the second time when they find it helpful.

We hope all these programs will make ICASSP 2009 not only the perfect occasion to exchange knowledge and experience, but also an outpouring of creativity and productivity.

The conference will be held at the Taipei International Convention Center (TICC). TICC is located at the center of Taipei city, just one block from the Taipei 101, which remains the highest building in the world through 2008: a bird's-eye view of the entire city from the top floor of the skyscraper is an extraordinary experience. While the Grand Hyatt Taipei, located adjacent to TICC, will be the conference hotel, enough rooms in several other hotels at different price levels have also been reserved for the conference; round-trip, free shuttles will be provided for participants staying in these other hotels.

Please make sure to join us for the Welcome Reception on the evening of April 20th in the Grand Ballroom of the Grand Hyatt Taipei, and for the Banquet at the Golden Dragon Grand Ballroom of the Grand Hotel on the evening of the 22nd. In both cases not only will you enjoy "real" Chinese food, but the culture programs will be exceptional and unique: please make sure to have your cameras ready. In particular, the Grand Hotel, in which the banquet will be held, is another of Taipei's magnificent landmarks: its traditional palace-style architecture and impressive lobby are unparalleled.

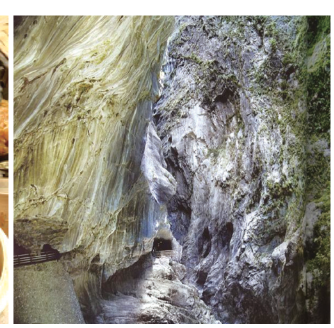
Taipei is a paradise for gourmets. A gourmet's map will be provided to help plan a different style for each meal, if so desired. Several sightseeing tours will also be offered; these can be reserved either in advance via the Internet, or on-site at the convention center. In particular, the half-day tour to the National Palace Museum to see the thousands of traditional Chinese treasures and the one-day tour to the Taroko Gorge National Park to see the 20 kilometers of marble cliffs are highly recommended. These are truly world-class, unique sites.

Finally, I would like to take this opportunity to thank all of our organizing committee members and all of our colleagues in the Conference Board of the Signal Processing Society for their support, help, and effort to realize this conference. Special thanks go to all of the technical committee chairs, liaisons and representatives, the review organizers, and the many reviewers for their diligent effort in reviewing the submissions, selecting the papers, and organizing the sessions. We would also like to thank all of the speakers and authors. Special thanks also go to the many local volunteers, helpers, and supporters in Taiwan. The knowledge, experience, wisdom, innovation, and efforts of those mentioned above are indeed reflected in this conference. Thank you very much.

We look forward to meeting you in Taipei soon.

Lin-shan Lee
General Chair, ICASSP 2009





A PORTABLE USB-BASED MIROPHONE ARRAY DEVICE FOR ROBUST SPEECH RECOGNITION

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ABSTRACT

We present a USB-based, highly directional, and portable microphone array device that delivers a crisp, clear and noise-reduced speech signal. This device consists of four linearly distributed microphone sensors and a filter-and-sum beamformer designed using broadband beam-forming algorithm. The device has a narrow acoustic beam pattern and identical frequency responses for almost all speech bands. In addition to beamforming, an adaptive noise reduction algorithm is used to further reduce the background noise. By utilizing both the spatial and temporal information, the SNR of speech signals is improved and speech recognition performance in noisy environments is significantly improved as reported in our experiments.

Index Terms **—** Microphone array, beamforming, noise reduction, robust speech recognition.

1. INTRODUCTION

A microphone array consists of multiple microphone sensors located at different positions. It can be used for both sound source location [1] and speech enhancement by processing the signals from each individual sensors [2][3]. While most of the current speech processing software can only use the temporal information, the designed device utilizes both the spatial and temporal information; thus, significantly improving speech recognition performance and robustness.

One of the major challenges in applying a microphone array in speech recognition is that speech is a wideband signal. The traditional narrowband beamforming techniques are not appropriate anymore [4]. The problem has been addressed by the spatial Fourier transform of a continuous aperture [5] and the joint optimization of the spatial and frequency response [6]. In these approaches, to keep the constant response over the wide frequency range, the array size is usually large; thus most of the prototypes or products using microphone arrays on the market are quite large and cannot be used as a portable device [7]. The large size of the array prevents the array products from broad applications, such as handheld devices, wireless handsets, and PDA. Another challenge of a microphone array compared to single close-talking microphones is the decreased performance in speech recognition because of the variation of their frequency responses [8]. These problems need to be addressed by improving the array design algorithms, in order to develop a portable and high performance device.

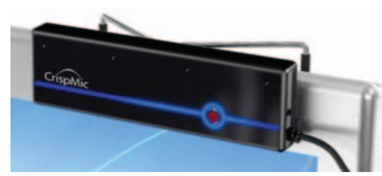

Figure 1. The 4-sensor microphone array named CrispMic™ clipped on a laptop

In this paper, we present a portable microphone array device, named CrispMic™, where both the size and performance have been properly addressed. As shown in Figure 1, the size of the microphone array is only 9.6 x 2.6 x 1.3 cm which is less than the half of the size of a similar microphone array on the market. Also, it has a constant frequency response in a wide range of speech bands as shown in Figure 4. The experimental results in this paper show that the array can improve speech recognition performances significantly, especially in noisy environments.

2. SYSTEM DESCRIPTION

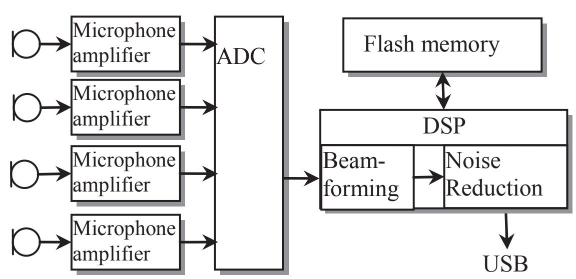

Figure 2. Illustration of the hardware structure

Figure 2 shows the structure of the device. It consists of four identical omni-directional microphones, an audio codec chip with an ADC and pre-amplifiers, a DSP (digital signal processor) chip, a flash memory and a USB interface. The acoustic signal is picked up by four microphone components arranged as a linear array with 20 mm intervals. The audio codec provides an adjustable gain, and converts the four channels of analog signals into digital signals for the DSP. The beamforming algorithm combines the 4 channels of speech into one channel and then a noise reduction algorithm is applied to further reduce the background noise. The processed clean speech signals are then transmitted to a laptop or PC through the USB interface.

The flash memory stores the software code for the DSP chip. Once the system boots up, the DSP chip reads the code from the flash memory into the internal memory and starts to execute the code. The device is powered through the USB. It is a plug-and-play device and can be used without installing any software. Since both the analogue and digital circuits are implemented in a small PCB, the circuit board was especially designed to avoid the noise interferences.

2. BROADBAND BEAMFORMING

Due to the special requirements in size and performance, we developed a robust, far-field broadband beamforming algorithm and implemented it in the DSP chip. The beamformer has a constant response in the speech frequency bands between 300-4000Hz. In theory, it can significantly improve spatial SNR of the speech signals without distortions in different frequency bands.

The linear microphone array configuration is shown in Figure 3. It is comprised of four equally spaced microphone sensors, where d_i is the distance between the i^{th} microphone and the center of the array. The output y of the array is the filter-and-sum of the four microphone outputs, $y = \sum_{n=1}^{4} w_n^T x_n$.

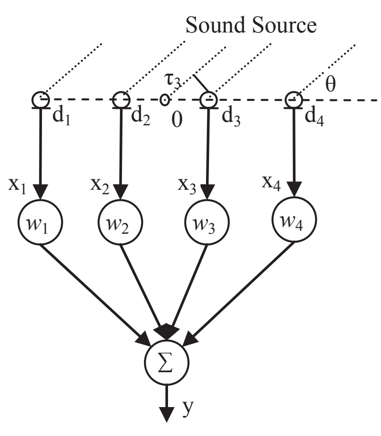

Figure 3. The configuration of linear microphone array.

The spatial directivity pattern $H(\omega,\theta)$ for the sound source form angle θ with normalized frequency ω is defined as [2]:

$$H(\omega,\theta) = \frac{Y(\omega,\theta)}{\bar{X}(\omega,\theta)} = \frac{\sum_{n=1}^{4} W_n(\omega) X_n(\omega,\theta)}{\bar{X}(\omega,\theta)} \quad (1)$$

where $\bar{X}$ is the signal received at the center of the array and W is the frequency response of the real-valued FIR filter w. If the sound source is far enough from the array, the difference between the signal received by the n^{th} microphone x_n and the center of the array is a pure delay. We use $\tau_n = f_s d_n \cos\theta / c$ to measure the delay by the number of samples, where f_s is the sampling frequency, c is sound speed, and $X_n(\omega,\tau) = \bar{X}(\omega,\theta) e^{-j\omega\tau_n}$ is the microphone signal. The spatial directivity pattern H can be re-written as:

$$H(\omega,\theta) = \sum_{n=1}^{4} W_n(\omega) e^{-j\omega\tau_n(\theta)} = \mathbf{w}^T \mathbf{g}(\omega,\theta) \quad (2)$$

where $\mathbf{w}^T = [\boldsymbol{w}_1^T, \boldsymbol{w}_2^T, \boldsymbol{w}_3^T, \boldsymbol{w}_4^T]$ and $\mathbf{g}(\omega,\theta)$ is the steering vector.

Let the desired spatial directivity pattern equal 1 in the pass band and 0 in the stop band. The cost function is then defined as:

$$J(w) = \int_{\Omega_p}\int_{\Theta_p} |H(\omega,\theta) - 1|^2 \, d\omega \, d\theta + \alpha \int_{\Omega_s}\int_{\Theta_s} |H(\omega,\theta)|^2 \, d\omega \, d\theta \quad (3)$$

Let $\partial J / \partial w = 0$. We can then obtain the best parameter set w.

A Computer simulation was conducted to verify the performance of our designed beamformer with the following parameters: The distance between microphones is 0.02m, the sampling frequency f_s = 48k, and FIR filter taper length L=128. When the pass-band (Θ_p, Ω_p) = {300-4000Hz, 70^o-110^o}, the designed spatial directivity pattern is 1. When the stop-band (Θ_s, Ω_s) = {300~4000Hz, 0^o~60^o+120^o~180^o}, the designed spatial directivity pattern is 0.

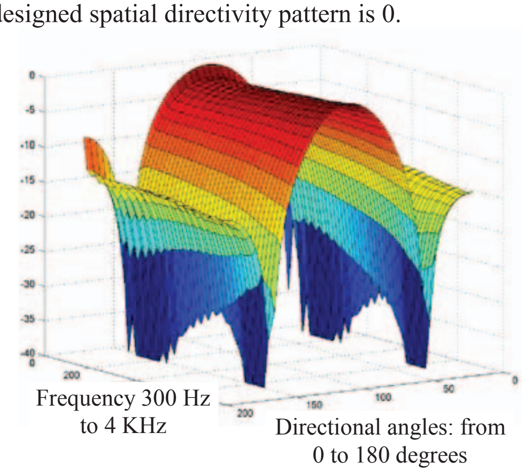

Figure 4. Directivity pattern of the designed microphone array: the frequency bands from 300 Hz to 4 kHz of the sound from the front of the microphone array are enhanced and the sound from other directions are reduced by about 15 dB.

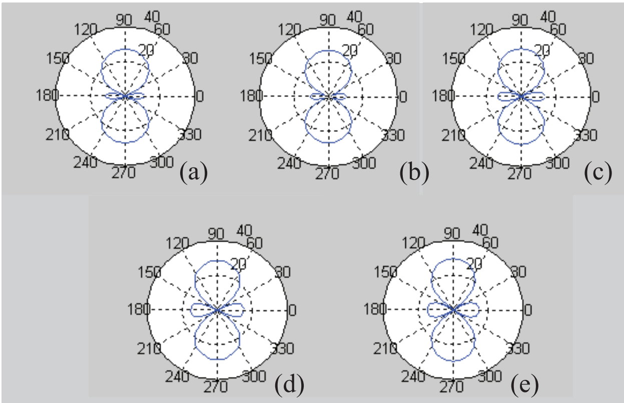

Figure 4. Computer simulation results for the designed 4-sensor microphone array: The directional response for frequencies of (a) 0.5, (b) 1.0, (c) 2.0, (d) 3.0, and (e) 4.0 KHz.

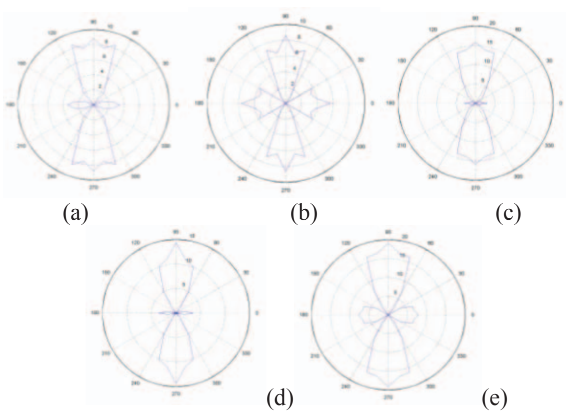

Figure 5. The directivity pattern of the microphone array based on our measurement in an anechoic chamber: The direction response for frequencies of (a) 0.5, (b) 1.0, (c) 2.0, (d) 3.0 and (e) 4.0 KHz. (The center is 0 dB.) The directional gains are significant and match the theoretical design and simulation.

Figure 4 shows the directivity pattern of designed microphone array. In all frequency bands, the main lobe has the same level, which means the speech signal has little distortion in frequency. The main lobe is about 15dB higher than the side lobe; therefore the background sound from other directions will be highly suppressed compared to the sound in the desired pass direction.

To verify the design simulation, we conducted an experiment to measure the spatial response of the microphone array in an anechoic chamber using a white noise stimulus. The microphone array was placed in a fix positioned and rotated in 20 degree increments. For each rotation, we applied the designed filter $\boldsymbol{w}_i$, i = 1,2,3 and 4, on the signal picked by each microphone and calculated the energy gain. The spatial directivity pattern is shown in Figure 5. The main lobe has a similar width among all the bands. The result shows that the directional gains are significant and are similar to our theoretical simulation.

3. NOISE REDUCTION

Our adaptive noise reduction algorithm consists of three key components: frequency analysis, adaptive Wiener filtering, and frequency synthesis. The frequency-analysis component is used for transforming the wideband noisy speech sequence into the frequency domain so that the subsequent analysis can be performed on a sub-band basis. This is achieved by the short-time discrete Fourier transform (DFT). The output from each frequency bin of the DFT represents one new complex valued time-series sample for the sub-band frequency range corresponding to that bin. The band width of each sub-band is given by the ratio of the sampling frequency to the transformed length.

The most crucial step of the temporal filtering technique is an adaptive Wiener filter, which estimates the clean-speech spectrum from the noisy-speech spectrum. The system explores the short-term and long-term statistics of noise and speech, as well as the segmental SNR, to support a Wiener gain filtering. The noisy-speech spectrum passes through the Wiener filter, which then generates an estimate of the clean-speech spectrum. In the last step, the frequency synthesis, as an inverse process of the frequency analysis, reconstructs the clean-speech signal given the estimated clean-speech spectrum.

5. ASR EXPERIMENTAL RESULTS

In order to verify the performance of the CrispMic™, we have conducted a sequence of experiments. The experimental configuration is shown in Figure 6. The recorded speech was played by an artificial mouth while the background noise was played by four loudspeakers.

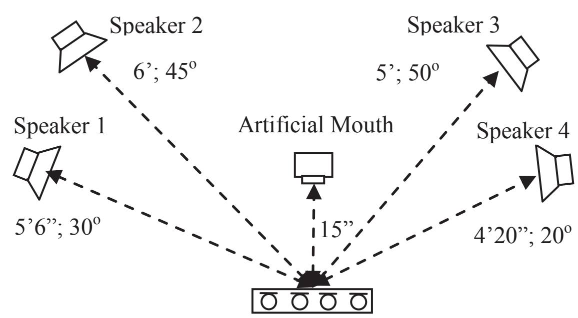

Figure 6. Experimental configuration

Experiment 1: Figure 7 shows the SNR improvement by using the CrispMic™. In this specific experiment, speech was played by an artificial mouth while white noise was played from Speaker 4 only as shown in Figure 6. Figure 7 (a) is the signal recorded by traditional omni-directional microphone, where the SNR is 3.3dB. Figure 7 (b) is the signal processed by beamforming. The SNR is increased about 31dB by the spatial approach. Figure 7 (c) is the signal after noise reduction, which is also the final output of the CrispMic™. SNR is further improved another 10dB by the temporal approach.

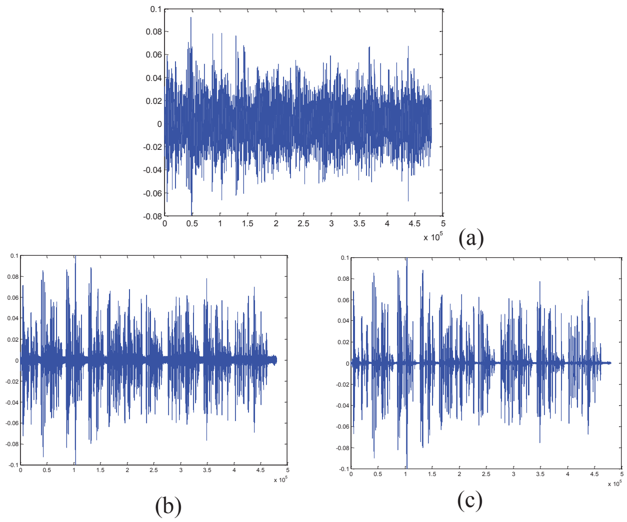

Figure 7. The improvements on SNR: (a) The original signal captured by a traditional mic, SNR = 3.3; (b) The signal after beamforming, SNR=36.9dB; and (d) The signal after noise reduction, SNR = 49.4.

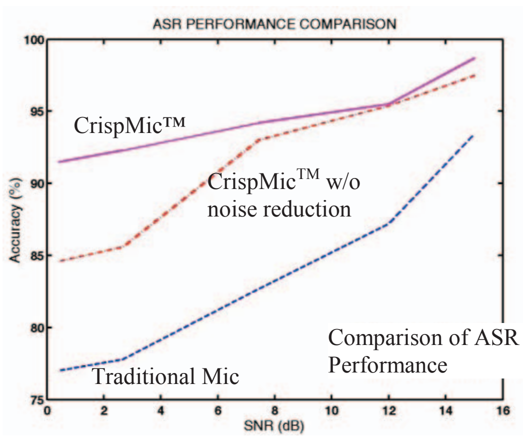

Figure 8. Comparison of ASR performance

Experiment 2: The CrispMic™ has also undergone a series of tests in the automatic speech recognition system and the performance is measured in terms of the recognition accuracy. In our experiments, background helicopter noise was played by four loudspeakers, Speakers 1-4 as in Figure 6. The CrispMic™ was connected to a laptop where Nuance's software was used for recognition. The experiments used 244 pre-recorded English phrases. During the test, if any word in the recognized phrase was different from the spoken phrase, we counted it as an error and the entire phrase was rejected. The experiment allowed for two attempts; if the first attempt failed, we allowed a second attempt using the same phrases to simulate the real applications. Our experimental results are plotted in Figure 8 and Table 1. The results showed that the contributions of our microphone array and noise reduction to speech recognition are very noteworthy.

Table 1. Comparison of Speech Recognition Performances on the CrispMic™: The number of loudspeakers is 4, the number of attempts is 2, and the number of test phrases is 244.

SNR (dB)	**0.40**	**2.66**	**7.44**	**11.99**	**15.01**
Traditional microphone (%)	77.0	77.9	82.7	87.2	93.4
LcT: 4-microphone array only (%)	84.6	85.6	93.0	95.4	97.5
CrispMic™: 4-mic array plus noise reduction (%)	91.5	92.3	94.2	95.5	98.7

4. CONCLUSIONS

In this paper, we presented a novel microphone array device. Compared to traditional microphones, the device utilizes both the spatial and temporal information; therefore it significantly improved SNR and speech recognition performance. Compared to the similar product or prototype on the market, this device is much smaller in size, which facilitates its application to portable devices, such as wireless phones, PDA, and Laptops.

5. ACKNOWLEDGEMENT

We would like to thank Jingdong Chen for useful discussions and Ashrith Deshpanda, Romnel Crasta, and Xiaoqian Xiao for conducting some of the experiments.

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