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IEEE President K. J. Ray Liu, "Follow Multiple Paths," Changing the World With Microwave Time Reversal Focusing

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(Special Series Paper)

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ABSTRACT This is the sixth in our Microwave Pioneer series in which we are privileged to provide our readers with a very special subject: current IEEE President K. J. Ray Liu. Professor Liu's inclusion in this series is not due to his position as leader of the IEEE, but rather to his influence and leadership in the field of indoor surveillance and tracking using microwaves. His discovery, demonstration, and application, of microwave multi-path time reversal focusing for use in positioning and tracking, when coupled with recent advances in wireless communications, are primed to have worldwide impact. The imminent roll-out of commercial systems through Professor Liu's company, Origin Wireless AI, could change the very nature of our society through its many potential applications in indoor monitoring, tracking, and motion sensing using existing Wi-Fi infrastructure. The implications for both improved security and health care in the home and office – as well as the accompanying controversies over issues of privacy, are profound. It is appropriate that an individual who has already had a considerable role in shaping our local signal processing and microwave fields, as well as the broader IEEE community, should extend his influence to our society at large. With 12 books, 18 book chapters, 6 special issue journal releases, more than 800 refereed journal and conference publications, over 70 patents and dozens of editorials and magazine pieces, you will certainly appreciate Professor Liu's multi-path impact as you read about his multi-path career!

INDEX TERMS Microwave Pioneers, Microwaves are Everywhere, K.J.R. Liu, IEEE President, multipath time reversal focusing, microwave surveillance, Odyssey, Origin Wireless AI, microwave fingerprinting, microwave motion detection, video over internet, TRRS.

I. INTRODUCTION

Setting out in one's career with the goal of changing the world is a lofty ambition for anyone, let alone an electrical engineer in academia. However, I think you may conclude, as I have, after reading this Microwave Pioneer interview article,[1] that Kuo-Juey Ray[2] Liu is about to do just that!

Born in Taichung in central Taiwan in 1961, as the first of four children, Ray was always good at mathematics. In secondary school he formulated a novel proof for an interesting property of triangles, which he later related to bandwidth properties of the Yagi-Uda antenna

[1]This article was composed after three fascinating Zoom-based interviews with Ray Liu on March 28th, 30th, and April 10th, 2022. Like our prior article on Carver Mead [1], we have chosen not to preface the title with "Microwave Pioneer" since Professor Liu made most of his contributions to signal processing (he is the author/co-author of 12 books on various subjects in signal processing and VLSI as well as wireless AI). However, the subject area which benefits most from his research happens to involve microwave wireless communications, specifically 4G, 5G and 6G devices and applications. The move to 5 GHz and beyond has increased the available bandwidth and the inherent resolution (cm scale focal spot diameter) of microwave systems and has enabled his breakthrough concepts on non-line-of-sight multi-path time reversal positioning and tracking to move into mainstream commercial applications that are poised to change the world!

[2]The Chinese character "Juey," appropriately meaning *doing very well*, is pronounced "Ray" in English, hence President Liu's choice of this Americanized version of his name, which he has used since his arrival in the United States in 1985 to do a master's degree at University of Michigan, Ann Arbor.

[2][3] and more generally the Log Periodic antenna [3]. This won him a math invention prize and he scored first in a mathematics competition in his high school.

Even pre-college, Ray was interested in real-world problems and applications, and it appeared to him that physics was the field that best took up the principles of mathematics and applied them to practical concerns. He was thus drawn to the hard sciences. As a senior in high school in 1978, Ray was required to declare a college-track focus or major that needed to be pre-approved by his parents. As it happened, Ray's father was a medical doctor, and he was insistent that his son follow in his footsteps. However, he hastily switched into engineering and science, despite his parents' trepidations. This decision would end up serving him very well!

In the mid 1970s, Taiwan had begun building up its interest and capabilities in semiconductor manufacturing with help from RCA [4] amongst other US companies. Electrical engineering was the discipline of choice for Taiwanese students who had skills in math and science, and National Taiwan University (NTU) was the place to be. Ray studied EE with a focus on electromagnetic wave propagation and graduated in 1983 with a desire to work on topics that involved lots of mathematics and physics.

During his time at NTU, Ray's parents migrated with his three siblings to the United States. After he finished university and his compulsory two-year military service, Ray joined them there in 1985 as a master's student at the University of Michigan, Ann Arbor. At Michigan, he was very motivated by mathematics professor, Jack L. Goldberg's linear programming course, where he remembers asking a very fundamental question about basis vectors and being laughed at by the entire class. When Goldberg responded to the question by stating that, "Only very few of those who have the insight, can ask this great question," Ray's confidence took a giant leap forward!

At Michigan, Ray ended up working on electro-optics and holography with renowned Michigan faculty member Emmet Leith.[4] Upon graduating, he received an offer from Bell Laboratories, but ultimately decided instead to undertake a PhD. His parents were in Los Angeles, California, so he applied to the doctoral program at UCLA. After being informed by UCLA EE Professor Kung Yao[5], who would become his thesis adviser, that his (Ray's) was the only University Fellowship granted by the department that year, he enthusiastically enrolled.

[3]Prof. Liu never published this result, but he still has the original proof and may yet decide to do so. He called the concept the Parallel Line in Triangle Theorem (see page 2 of [3]) and it involves lining up of the intersecting points on crisscrossing parallel lines emanating from the intersection of these lines with the two sides of an arbitrary triangle. For an isosceles triangle, the intersections form a bisecting line from the vertex to the midpoint of the opposite side and the parallel lines map out a Yagi-Uda antenna.

[4]Emmett Leith demonstrated 3D holography in 1964 and was the recipient of the National Medal of Science. He worked and taught at University of Michigan from 1952 almost until his passing in 2005 at age 78 [5].

[5]Kung Yao was an EE professor at UCLA from 1966-2015. He is best known for his work on signal processing and VLSI and is co-author of the two-volume text on these subjects (with K.J. Ray Liu [6].

Ray arrived in Los Angeles in July 1987 and threw himself into his studies. In less than three years, he already had a completed thesis [7], nine conference papers [8]–[16], three journal publications [17]–[19], and five book chapters [20]–[24]! Professor Yao advised him to pursue a career in academia and Ray began looking for a teaching position in early 1990. It was a very tight job market, and Ray was fortunate to get an offer at University of Maryland (UMD), College Park. He again crossed the country - this time with a wife and new son in tow - to begin the academic portion of what was to become a multi-path career that would last through the next three decades.

His first few years at UMD were difficult. Grant money was tight (there was a deep recession in the US at the time), and he did not know about, and therefore had not negotiated for any start-up funding. He began submitting multiple proposals to a variety of government agencies and started up collaborations with several industrial partners. In the meantime, Ray continued working on VLSI and signal processing with his students at UMD and with former colleagues from UCLA [25]–[35]. The culmination of much of his VLSI signal processing work was summarized in an invited PROCEEDINGS OF THE IEEE paper that came out in 1998 [36], and a two volume text he later wrote with his former thesis adviser and now colleague, Kung Yao [6].

In 1984, Ray was awarded a National Young Investigator award, and at the same time he landed an NSF grant. He also applied for a multi-year National Institutes of Health R01 research grant (for the first time) to work on multidimensional NMR data analysis [37], [38]. After receiving a notice from NIH that his priority score was 117 and his percentage rank was only 0.8, he tossed out the message, totally dejected. It was only after talking to a colleague that he realized a very high score on priority and a very low percentage ranking on an NIH application, meant his grant was ranked at the very top, and guaranteed for funding!

Ray's research career began to take off at this point and he was heavily focused on VLSI design, algorithms, and signal processing techniques [39]–[46]**.** In 1996, he was able to take a sabbatical at Stanford University, Palo Alto, California, where he became involved with a friend and colleague who was working on a VLSI-focused start-up company in Silicon Valley. The goal was to design and implement a video encoder chip that could take advantage of the new H.263 video compression standard for signal transmission over modems and twin-wire telephone lines. H.263 was the video portion of the new 1995 International Telecommunications Union (ITU) H.324 media standard.[6] At the time, it took two or more chips to perform the required data compression and communications protocols. Ray led a team which successfully developed

[6]The H.324 standard was an International Telecommunications Union protocol ratified in 1995. It specifies how video, speech, and data would be distributed over a modem and single analog telephone line. H.324 was aimed mostly at teleconferencing. Part of the protocol was the H.263 video compression standard that targeted video conferencing [47].

a single VLSI chip to perform the video compression and in the process, he learned a lot about start-up companies.

When Professor Liu returned to the University of Maryland in 1997, he was still very excited about the idea of being able to transmit video over existing modem and telephone infrastructure. He teamed up with others to form a small company in Jessup Maryland which he named Odyssey Technologies. Ray's concept however, was nothing short of revolutionary. He wanted to turn existing computers into digital surveillance nodes that could capture video through a direct wired or integrated laptop camera, compress it, store it, view it, and transmit it, in real time over the existing wired network. However, computers at the time had typical CPU clock rates of only around 100 MHz, completely inadequate for real time video encoding. Over the next two years, with his knowledge of VLSI, signal compression, and software, Ray and his small start-up of about 20 people, developed a complete software-based multimedia video platform that could perform video conferencing, video email, DVD playback, and remote digital surveillance, all based on ultra-fast software and specialized algorithms. He introduced his video conferencing product as the "Odyssey Multimedia Gallery" and his surveillance system as "Remote Eyes". His first two rounds of venture capital fund raising brought in several million dollars and he was well on the way to making it very big in the start-up world. A composite slide assembled from one of his venture capital funding presentations in 1999, is shown in Fig. 1.

By 1999, Ray was already on round three of his venture capital funding and he had interested more than a dozen Fortune 500 companies, including IBM, which was implementing his Multimedia Gallery in its high-end Thinkpad^{TM} laptops. It looked like Odyssey, which was already profitable after only two years, was about to launch a digital imaging revolution! The funding pitch also included projections as to how Remote Eyes platforms could take advantage of rapidly improving CPU speeds to offer 40 frames per second of video imaging by the year 2000. The next step for the company was to take the leap into marketing and sales and to spur major growth. At this point Ray had planned to step back – at least partially – into his teaching career, while maintaining a working involvement and a seat on the board of the growing company. In turn, the board brought on a new CEO.

Without going into details, suffice it to say that the new CEO took the company in a direction that did not result in the projected growth that was anticipated. Ray was so upset by the new leadership at Odyssey, that he resigned from the board and returned fully to his academic teaching and research. When the board came back to him in May 2001 (after replacing the errant CEO), to ask for his help and to again take on a leadership role at Odyssey, Ray declined. By then competitors had caught up with the Odyssey technologies, and there were insufficient patent protections to keep a lock on the algorithms. After the 911 terrorist attacks on the two World Trade towers in New York City in September 2001, the demand for digital security solutions skyrocketed. Odyssey missed out on its chance to become a major player, and went

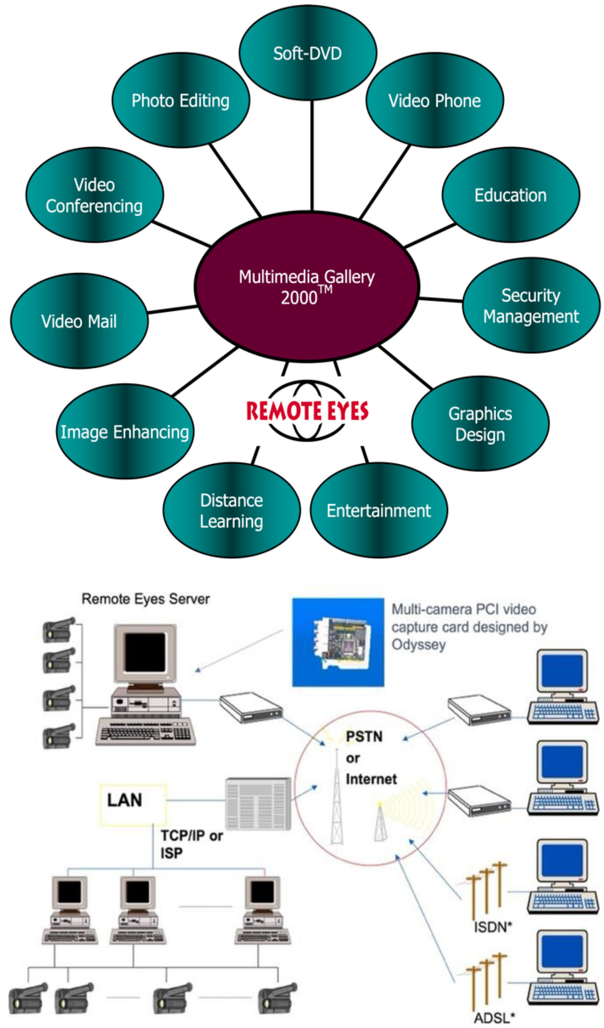

FIGURE 1. A composite from Ray Liu's VC funding presentation in 1999 showing some of his revolutionary concepts for Odyssey, which had already been integrated into IBMs high end Thinkpad^{TM} laptops. Image courtesy K.J.R. Liu, March 2022, with permission.

from a potential *unicorn* to one of many smaller companies supplying digital security solutions.

Before leaving this very intriguing period of Ray's career, it is worth reiterating the very revolutionary nature of his vision back in 1997. He was indeed the very first to conceive, develop, and deliver commercially, an all-digital and software-based media-over-internet platform for imaging and surveillance at a time when existing systems were still based on analog capture and storage devices. This digital revolution in the security industry, which he played a large part in starting, has since exploded and has been the basis of today's ubiquitous uses of surveillance. Fortunately, Ray would get a second chance at start-up prominence a bit later in his career.

Back at University of Maryland in the late 1990s, Ray began focusing his research activities on the burgeoning field of wireless communications, and in particular, large base-station arrays. A major result of this emphasis was the pioneering development of the concept of duality between uplink and downlink networks for joint transmit beamforming and power control that could increase the number of viable users in a cellular network by over a hundred times [48], [49]. His many technical papers inspired decades of research and development in cross-layer optimization of MIMO (multiple-input multiple-output) wireless networks that impacted much of wireless communications system design [50].

Starting in the early 2000s, Ray and his group at UMD began looking into new areas of wireless signal handling. His team was the first to design a code that achieves the maximum space, time, and frequency diversity [51]. He also developed digital key management and distribution protocols for secure communications in wireless networks [52], [53], and used Game Theory[7] to optimize resource allocations for wireless communications [54]–[57]. In addition, he proposed a novel framework to model and evaluate trust-over-networks based on information theory [58].

One topic of particular interest during this period was cooperative communications, wherein wireless networks and devices employ signal use synergy to improve performance. Ray was among the earliest to recognize that its impact would be far-reaching, and he set forth to show how it could improve communication performance, expand transmission coverage, provide energy efficiency, extend network lifetime, and increase signal throughput and stability in multiple access schemes. The author cannot do justice to the enormous technical content generated by Ray and his students on this topic. A summary of his many contributions and papers in this field appear in his major monograph, "*Cooperative Communications and Networking*," Cambridge University Press [59] which was published in 2008. Ray was also among the first to employ Game Theory for devising optimal solutions and strategies in cognitive radio, wherein a transceiver searches for and detects channels that are not in use and allocates them for immediate purpose (dynamic spectrum access). At the same time it minimizes interference, enhances spectrum sharing, increases security, and helps with anti-jamming. Amongst the prolific outpouring of journal and conference articles is Ray's comprehensive text, "*Cognitive Radio Networking and Security: A Game Theoretical View*," Cambridge University Press [60], which came out in 2010.

In addition to his large volume of research papers and books, Ray worked with IEEE to help launch a new multi-society sponsored journal, IEEE Transactions on Multimedia, in 1997 (first issue released in March 1999). This spurred his interest in technical journal publishing and he followed up with Hindawi Publishing Corp., Cairo, Egypt, shortly after their founding in 1997, to start the journal EURASIP Journal on Advances in Signal Processing (JASP) in 2001, as Founding Editor-in-Chief. EURASIP JASP was acquired by Springer Nature, Switzerland AG, in 2007, and remains in their portfolio of communications journals. Ray was also recruited to head IEEE Signal Processing Magazine as their new Editor-in-Chief from 2003-2005, a position he remembers very fondly. He then served as vice-President of Publications for the IEEE Signal Processing Society from 2006-2008, where he participated in proposals to found two more very successful journals: IEEE Transactions on Information Forensics and Security (2006) and IEEE Journal of Selected Topics in Signal Processing (2007). Ray also took on the reigns of President of the IEEE Signal Processing Society from 2012–2013, a major stepping stone on his continuous climb to the Presidency of the IEEE!

Back at the laboratory, Professor Liu and his students began to delve into another trendy research area - less related to digital signal processing, but very relevant to the growing market in the dissemination of digital information. This involved safeguarding, tracking, and fingerprinting, both digital media and digital networks, through covertly embedded codes and special trust algorithms [61]. Ray coined the term "information forensics" when he proposed the journal under this nomenclature (IEEE Transactions on Information Forensics and Security). Again, the author cannot do justice in this short write up to Ray's prolific outpouring of publications on these subjects, and only his two books: [62] and [63], followed by a short list of some of his more popular journal articles: [64]–[73] are included in the references. For those who want a less technical summary of this specialized area of his research, references [65] and [73] are suggested.

It is at this juncture, the late 2000s, when we finally arrive at the subject on which this article was conceived: *microwave multipath time reversal focusing using wireless signal processing*. In 2009, the US Defense Advanced Research Projects Agency (DARPA) approached Professor Liu through a colleague who knew about his wireless communications work, and asked if he (Ray) would be interested in trying to tackle a particularly hard to solve problem the Navy was having. They wanted to be able to have stable internal wireless communications throughout their fleet of submarines, which as you are undoubtedly aware, are composed mostly of metal rooms, metal furnishings, and similarly constructed metal doorways – not an ideal environment for efficiently propagating radio frequencies!

Ray was aware of a prior DARPA program that was based on an interesting acoustic theorem known as *time reversal focusing*, which had been demonstrated in the 1990s as a technique for locating and interrogating hidden objects by recording the received time response of a transmitted impulse function from an unlocated object, digitizing and time reversing it, then transmitting the time-reversed sequence back through the same medium. This results in individual time-delayed signal paths coherently adding and focusing at their point of origin. If the time reversed signal is convoluted with the original impulse, a single power peak appears at the precise location of the transmitter [74]–[77] thus enhancing the

[7]Game Theory uses mathematical models to analyze interactions and decision making typically amongst individuals or groups, but also animals and computers. It is most widely employed and recognized in the field of economics, but has applications in any field where rational decision making has a role in the outcome of a cooperative problem.

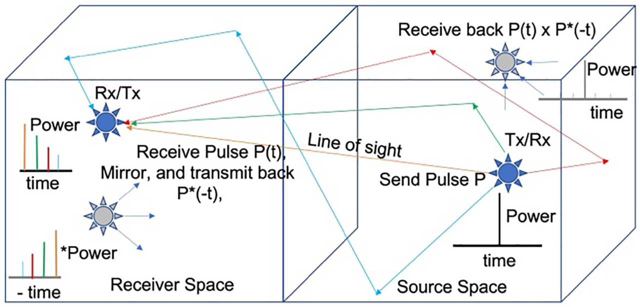

FIGURE 2. **An illustration of the multipath time reversal focusing concept. The gray "stars" are shifted from their nominal blue "star" positions for illustration only. At every point in the receiver space the convolution of the conjugated and time reversed signal with the transmitted impulse function yields a peak at the position of the source (Tx/Rx). The more multipath signals that can be collected at the receiver (Rx/Tx), time-reversed, and transmitted back through the identical spatial environment, the tighter the focal spot and the higher the power. Every spatial point in the receiver domain has a unique signature.**

signal strength at a specific spot, and enabling location of the transmitting object. This original acoustic technique had been suggested for electromagnetic waves in 1999 [78], and demonstrated in 2004 [79] in the ISM (industrial, scientific and medical) band at 2.45 GHz by groups at CNRS in France [74]–[79] and Carnegie Mellon University in the US [80].

The beauty of the technique, as far as Ray's DARPA problem was concerned, is that the more reflections the waves underwent on their path from transmitter to receiver (highly characteristic of the submarine environment), the more time resolved data points were present in the received signal, and the more tightly focused the time-reversed re-transmitted signal became. If enough multipath signals could be captured and time reversed, they would all coalesce into a single wavelength-scale focal spot – perhaps in another room – where they formed a concentration of power that could be leveraged to improve the wireless propagation in the highly reflective environment the Navy was concerned with. The concept is illustrated in Fig. 2.

Time reversal focusing was an intriguing application of signal processing that seemed ideally suited to, but not yet exploited in the wireless world because the bandwidth available was not large enough to capture a significant number of multipath signals. For the DARPA program, Professor Liu worked with a team to develop a prototype test bed that used time reversal focusing to significantly improve the signal propagation in the severely constrained multipath environment and realized a significant gain in signal-to-noise. However, the transceivers he designed and realized for the DARPA application (because of the large required bandwidth and fast A/D and D/A circuits this necessitated) were too costly for implementing in a commercial application – more than $15000 per unit.

As a result of this project, Ray became fascinated by the time-reversal physics that resulted in all the multipath energy focusing into a single tight sphere. From a system theory viewpoint, this technique used the environment as a "computer" to perform a perfect deconvolution of a complex multipath signal that was not possible using digital signal processing techniques. It made Ray wonder if such a technique could be applied more generally than in the confines of a submarine, and perhaps be of broader benefit to humanity. Although the DARPA results were not published, Ray and his students further developed the concepts that form part of three widely cited papers [81]–[83], as well as Professor Liu's very comprehensive text on this subject, "*Wireless AI, Wireless Sensing, Positioning, IoT, and Communications*," NY, Cambridge University Press, which was just recently published in 2019 [84].

Before delving headlong into microwave multipath time-reversal focusing, the author just wants to mention that between 2009 and present day, Professor Liu continued his prolific university research in many crisscrossing areas of digital signal processing, producing more than 200 journal papers, 160 conference articles, 65 patents (with many more still pending), a dozen editorial articles, and yet another recent text in 2021 on Game Theory [85] inspired by biological reciprocity and evolution theory and his development of the Chinese Restaurant Game family for decision making in network and data science! Here again, the author cannot hope to do justice to the scope and quantity of all this research. In addition to the many articles on Game Theory and its applications in shared communications [86]–[113], cognitive radio [114]–[123], and information forensics [68], [71], [124]–[130], Professor Liu and his students and colleagues also focused on wireless energy harvesting, both without [131]–[134], and in conjunction with time-reversal focusing [81], [82], [135], as well as other topics in signal processing [136]–[145]. Only a smattering of the most cited journal references are shown and twice as many conference papers accompany these!

For our microwave focused audience, however, the emphasis in this write up is on microwave multipath time reversal focusing. As already mentioned, the idea for this research path came out of the work Professor Liu had done for the Navy on improving wireless communications inside spaces with large multipath parasitics. The epiphany – of treating these multipath signals as positive characteristics, rather than trying to eliminate them as most of the signal processing world was doing at the time, is what led to the commercial technology breakthrough that Ray was craving after his missed opportunity with Odyssey.

Ray's group started to focus intensely on the application of time reversal (TR) focusing after 2010. They began with the idea of using TR to concentrate the power in low energy communications environments [81], [82] and came up with time-reversal division multiple access (TRDMA) multiplexing of signals [83] in 2012. This technique enabled high wireless data rates with low computational complexity [146]–[148].

While beginning to realize the potential of the technology, Ray quietly formed another start-up company in January 2013 at UMD's incubation center, which he called *Origin Wireless*,

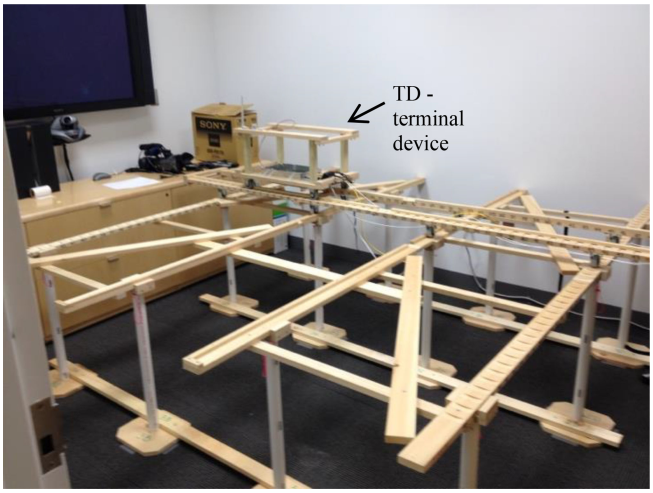

FIGURE 3. Experimental structure for moving the terminal device (TD) around the target space and recording the multipath time varying signature from the transmitting source impulse function at every point. (Image courtesy K. J. R. Liu, Aril 2022, with permission).

in reference to the focal spot formed by time reversed multipath signals at their point of *origin*. The big breakthrough came in 2014 when Ray and his group were experimenting in their lab with an indoor mock-up of a TR measurement system. This allowed them to electromagnetically probe various spatial positions with a terminal device (TD) that recorded time of arrival, the exact time difference between transmission and detection, and the angle of arrival, while a transmitter was broadcasting from a remote location. The set-up is shown in Fig. 3.

It was already well established that time of flight, signal strength, and triangulation methods could be used in wireless networks to locate a terminal device that was receiving and transmitting signal trains. However, these location techniques generally require multiple sources (at least three for direct triangulation) and the accuracy is typically limited to meters. The best achievable accuracy at the time using a range of very sophisticated techniques, was approximately one-half meter, but it required multiple transmitters and serious computation [149], [150]. Ray and his students had already established that the time domain signature from a transmitted impulse in a strong multipath environment was unique at every location within that environment [81]. In a landmark paper in 2015 [151], they used this TR focusing feature to demonstrate zero error rate position sensing and tracking at the $<$10 cm scale with only a single transmitter and terminal device in a completely non-line-of-site (NLOS) environment at 5.4 GHz!

Ray suddenly realized that they had the solution to the decades-old conundrum of the microwave-based indoor positioning problem, where the curse of meter accuracy was a result of having only three degrees of freedom from triangulation, and the technique only works under line-of-sight conditions. In contrast, TR focusing leverages hundreds or even thousands of degrees of freedom (multipaths) resulting in much higher location accuracy while functioning in a complete NLOS environment.

Their technique, and the very fast algorithm Ray and his group developed, required a priori mapping of the terminal device (TD) space and then direct comparison of the recorded and processed time reversal (TR) waveforms with the map in order to determine the TD location. However, the strong time reversal focusing effect and the wavelength scale of the power spot makes it extremely simple to correlate the processed TD signals with the map. Only total power level is needed, and because the signal level rises so substantially within the TR focusing region, signals from adjacent spatial domains are largely uncorrelated. This means that if there is a disturbance in the environment of the TD that changes the multipath signaling in some way, so long as the disturbance is at least a wavelength away from the TD, it has only a minimal impact on the TR signal strength derived from the TD. There is also a direct relationship between the bandwidth of the transceivers and the TR focal spot diameter. The time resolution of the TD determines the number of individual multipath rays that can be separately detected and the smaller the temporal signal spacing, the tighter the spatial power spot becomes (for the THz engineers in the room, larger spatial sampling of an interferogram results in finer frequency resolution as in a Fourier transform spectrometer). The initial position sensing system of [151] employed a bandwidth of 125 MHz centered at 5.4 GHz (ISM band) and produced a TR spot size close to a wavelength. Actually, TR spot sizes much smaller than a wavelength are possible [80].

Ray's very prescient insight, especially regarding commercialization of the TR technique, was to utilize existing Wi-Fi infrastructure rather than specialized equipment that would have to be installed in individual environments. Unfortunately, 802.11n chipsets utilize 20 or 40 MHz native bandwidth which is insufficient to realize the positioning resolution Ray had achieved in [151]. However, with clever uses of both frequency [152], and spatial [153] diversity, Ray and his team were able to increase the useful "effective" bandwidth of existing Wi-Fi networks to more than 300 MHz and realize, for the first time, spatial resolution and near error free positioning of TD devices at the one cm scale [152], [153]! Reference [153] includes detailed bandwidth and spatial resolution tradeoffs, effects of confounding environmental changes, source-transmit distance variations, and other performance impacting metrics.

Also key to this advance, was the very simple and fast signal processing algorithm that Ray and his team developed to record and compare the TR signatures from separate TD spatial cells that relied mostly on amplitude only, which he defined as the time-reversal resonating strength (TRRS). The TRRS is extremely fast to calculate in software, does not require an inordinate amount of memory, and the hardware components either exist or can be readily added to Wi-Fi networks or routers. TRRS is related to the cross-correlation between two sampled locations and the total energy in each temporal channel [84], [154] by:

$$\text{TRRS} \equiv \gamma\left[\boldsymbol{H}, \boldsymbol{H}'\right] = \left(\frac{\eta}{\sqrt{\Lambda}\sqrt{\Lambda'}}\right)^2 \quad (1)$$

where

$$\eta = \max_{\phi} \left|\sum_{k=1}^{K} H_k H_k'^{*} \mathrm{e}^{-jk\phi}\right|,$$

$$\Lambda = \sum_{k=1}^{K} |H_k|^2, \text{ and } \Lambda' = \sum_{k=1}^{K} \left|H'_k\right|^2.$$

H and ***H'*** are the channel frequency responses in two measurement cells, η is the cross-correlation between ***H*** and ***H'*** with modifications for phase distortion, H_k and H_k' are the impulse responses for subcarrier *k* or the channel state information (CSI), *K* represents the number of subcarrier channels (in a frequency combined system), and Λ, Λ' are the energies in each channel ***H*** and ***H'***.

At this point Professor Liu also realized the potential of microwave TR to record changes in the TD environment. In working with the test chamber he had established (Fig. 3), Ray found that, for example, when a door opened or closed it sufficiently changed the multipath environment that the change could be recorded through subtle differences in the collected channel state information or CSI – the Fourier transform of the channel impulse response. Through monitoring the CSI over time, learning and cataloging the impact of various events on the individual temporal waveforms, and adding some a priori training to his TRRS algorithms, it was possible to use the TR approach to recognize and record specific events within the TD space – for example the said door opening or closing, a person walking about, or the movement of an arm or hand by an otherwise stationary individual [155]–[157]. The measurement technique was even sensitive enough to detect very small repetitive spatial changes, such as those induced in the TD environment by human chest cavity movements during breathing [158]. Such repetitive movements or periodic changes, once the software was trained to detect them, could be used for biometrics [158]–[160]. Note that these events were all being measured without line-of-sight sensors and using existing Wi-Fi infrastructure! An easy-to-read summary of this expanding pool of TR applications can be found in [161].

A major breakthrough about the nature of the TR focusing sphere came out in October 2018, when Ray and his students published perhaps the most intrinsically significant characteristic of the TR technique which they called: Wiball [162] (provisional patent submitted in July 2016 [163]). They proved that when there is a large enough number of multipath signals, the TR focusing ball exhibits a stationary behavior in its energy distribution from the correlation point of view. Specifically, they realized that in the limit of large time-resolved multipath signals, the TR spot has spatially independent structure that follows a Bessel function power distribution [162]: $\eta\ (d) \approx J_0^2\ (kd)$, where *k* is the Bessel function coefficient, and *d* is the distance between any two points in the TD space. This means that the TR spot structure is inherently location and environment *independent*. Thus the distance an object carrying a receiver has moved within the TD space, as well as its speed, can be determined from the shape (individual peaks or valleys) of the TRRS focusing sphere produced at the receiver (TD) by a remote fixed transmitter broadcasting an impulse function. Multiple targets can be accurately and simultaneously tracked using a single transmitter, so long as they are more than a wavelength apart.

Another even more groundbreaking discovery in microwave TR applications was published in June 2018, when Ray and his team came out with the concept of WiSpeed [164] (provisional patent granted in Sept. 2017 [165]). The WiSpeed idea actually followed WiBall but came out earlier in the publication queue.

WiBall is based around one or more active transmitters that generate the TRRS focusing sphere through the receipt, by one or more TDs, of a transmitted impulse that undergoes multiple bounces in the NLOS space. In another truly inspired epiphany, Ray looked at what happens to the TRRS when there is no active source, but where an object is moving about in a geometric space filled with a Wi-Fi signal from one or more fixed Wi-Fi devices. If the moving object (TD) is treated as a reflector consisting of many virtual sources, and a statistical treatment is used to establish the impact of the electromagnetic fields from all these sources in forming a virtual TR sphere, it turns out that the autocorrelation function of these fields, as the TD moves through the space, has the same form of TRRS as expressed in equation (1). WiSpeed can be viewed as a virtual version of Wiball and relies on a virtual TR focusing effect through a virtual TRRS. That is, *no* active source need be present to derive the speed of the moving object!

As an example, when the signals received by a set of fixed commercial 802.11n-based Wi-Fi devices in a strong multipath environment change due to an object moving through the environment, the speed of the object shows up as a change in the Wi-Fi power spectrum over short time intervals. The cross correlated signals from the moving object $\eta\ (d)$ correlate with a natural peak in the differential fields. No a priori mapping of the fields or training of the system is necessary and for periodic motions, such as a person walking, it is possible to derive the average speed and the characteristic gait length. The system can also detect rapid motions, such as a person falling, and requires no special hardware. Experiments showed that speeds as fast as 2 meters/sec could be measured with 95% accuracy at a 200 Hz sampling (sounding) rate. Both distance of travel and accelerations could also be tracked. Since the algorithm uses peak detection for the autocorrelation function, and does not require any complex Fourier transforms, it uses minimal CPU overhead and can be implemented through a

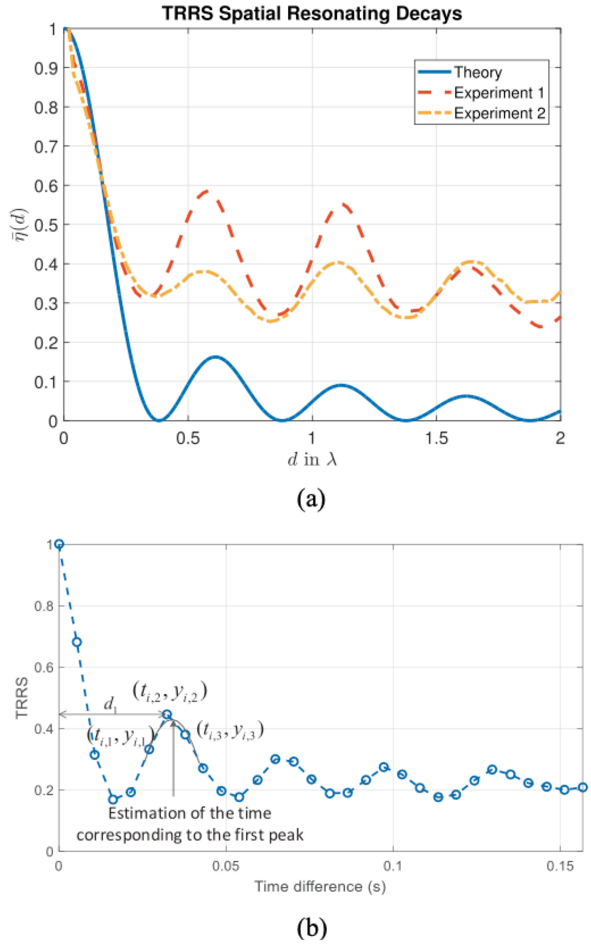

FIGURE 4. **(a). Cross correlation coefficient in the TR spot at different spatial locations within a scene for locations separated by 10 meters (dashed curves) and the theoretical distribution (solid curve). The offset on the experimental positions is due to line-of-sight energy paths not present in the theory, which assumes only scattered energy received at the terminal device (TD). (b). Peak detection based on the time difference for signals reaching the TD from the transmitter deconvolved into distance (and hence speed) utilizing the independent waveform shape at any position. Reproduced from [162], Fig. 4, ©IEEE, with permission.**

modest PC or even through Cloud computing. Higher speeds can be detected with higher sampling (sounding) rates.

The WiBall concept is illustrated in Fig. 4, reproduced from [162]. The DC offset in the dashed curves is due to the line-of-sight contribution to η. The accurate estimate of speed can be leveraged for indoor tracking. The position accuracy is based on the bandwidth and center frequency (125 MHz and 5.8 GHz in this instance). The range of measurable speeds and tracking accuracy are set by the frequency of the transmitting beacon (5 msec broadcast interval). No a priori mapping or training is required, but the tracking accuracy can be significantly improved if the location of some key objects in the space (such as corridor entries or pillars) are predetermined and used to correct cumulative errors in the algorithms. In the paper [162], both human tracking in a complex office-style environment and the highly accurate tracking of a small electric toy train continuously moving along a track were demonstrated with high (>95%) accuracy!

The discovery of WiBall and WiSpeed, and the subsequent algorithm implementation in a real environment with commercially available radio transmitters and receivers, represented the first non-line-of-sight, non-triangulation technique, for accurate position and speed estimation. Ray's TR technique represents a unique solution to the almost two-century long quest for some new physics that could equal, and in this case surpass, the ubiquitous frequency vs. speed relationship between a moving object and a wave-based source first described by Christian Doppler in 1842 [166]! Not only can an object's speed be measured in a cluttered environment, but microwave multipath TR enables accurate tracking of an unlimited number of subjects, indoors, and without costly infrastructure or a priori measurements.

Ray's team focused on the WiSpeed discovery as the basis for most of their subsequent work on wireless sensing because there was no requirement for an active impulse source. They developed both hardware and software and participated in real-world demos at the likes of Qualcomm, Apple, Marvell, Verizon, Linksys, Belkin, and almost every major tech company and government entity one could wish to have as an interested investor in a new invention. The TR-based software algorithms and corresponding applications Ray and his Origin Wireless AI group have since come up with, appear to be endless: indoor tracking [167], [168]; gait determination [169], [170]; motion detection for security [171]; sleep monitoring [172]; monitoring small motions inside a car [173]; material sensing [174]; monitoring heartrate and breathing [175]; heartrate variability detection [176]; fall detection [177]; recognizing and counting people in hidden spaces [178]; millimeter wave imaging [179]; millimeter-wave real time handwriting tracking and analysis [180]; and millimeter-wave keyboard tracking [181]; and sound detection [182], and this is just the start!

The burgeoning 5G/6G cellular and Wi-Fi rollouts will only make Ray's microwave TR technique more accurate, due to the increased bandwidth and higher carrier frequency, and IoT will add applications capability to every environment we inhabit. In a very recent preprint, Ray's TR method was demonstrated at 270 GHz with millimeter-scale positioning accuracy [183]! The stage has been set for Origin Wireless AI to become the unicorn that Ray had hoped for with Odyssey. A 2019 bubble diagram for Origin is reproduced in Fig. 5 as a companion to Fig. 1.

After a thirty-one-year long career in education, Professor Liu retired from his UMD position at the end of 2021 and is now devoting his attention to his growing company and its many products and potentially world-changing applications. One would think that this was enough of a time sink to keep him from doing anything else. However, despite the demands of the company and its burgeoning list of financial backers, the ballooning staff, the continuous raising of capital, and the setting up of expansive office and laboratory facilities, in 2020, Ray was enthusiastically nominated by his IEEE

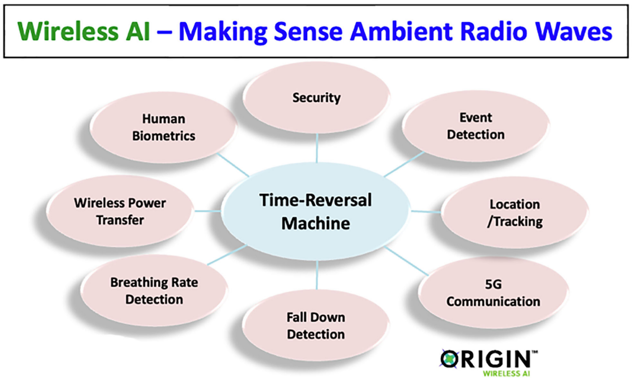

FIGURE 5. Applications bubble chart for Origin Wireless AI. Courtesy K.J.R. Liu, April 2022, w/perm.

colleagues and found the time to run for, and become the President elect (2021), and now the President and CEO of IEEE – an organization with over 400, 000 members and more than 1, 000 staff!

I cannot fathom where Ray gets the time for all his commitments, unless TR can also create clones - after all, it does involve time reversal! With all of this on his plate, Ray is approachable, empathetic, concerned about improving the world we inhabit, and as humble as they come. If all of his professional business and academic talents weren't sufficient, he also loves to travel, to garden, to cook – especially international cuisines – and he is as approachable and "homey" as the motto he created for his IEEE Presidency: "*Make IEEE Your Professional Home*."

Still in his early 60s, there is no telling how much more K.J. Ray Liu will change the world. As he brings the magic of microwave multipath time reversal focusing to us all, it is appropriate to finish this article with a favored quote of Ray's: "*Do Extraordinary Things; but Be an Ordinary Person.*" He has certainly lived up to this standard. I cannot think of a better role model for any technical or scientific field!

SUBJECT BIO

K. J. RAY LIU (Fellow, IEEE) received the B.S. degree in electrical engineering from Taiwan National University, Taipei, Taiwan, in 1983, and the Ph.D. degree in electrical engineering from the University of California, Los Angeles, Los Angeles, CA, USA, in 1990. He was a Distinguished University Professor, Distinguished Scholar-Teacher, and Christine Kim Eminent Professor of information technology with the University of Maryland, College Park, MD, USA, from where he retired at the end of 2021 after more than three decades of career in education.

He has authored or coauthored more than ten books and 800 refereed papers in his research areas, which include broad aspects of signal processing and communications, including wireless sensing, indoor positioning/tracking, wireless communications, network science, multimedia signal processing, information forensics and security, bioinformatics, and signal processing algorithms and architectures

Over the past decades, he has trained more than 70 Ph.D. and postdoctoral students, of which ten are currently IEEE fellows, about 30 of whom are with major universities worldwide, and the rest are entrepreneurs or active members in industry.

Dr. Liu is the founder and CEO of Origin AI that pioneers AI for wireless sensing and indoor tracking. The inventions/technology /products of wireless AI won three prestigious CES Innovation Awards, including CES Best of Innovation in 2021, 2017 CEATEC Grand Prix, and 2020 Red Dot Design Award, and among other awards.

He is the 2022 IEEE President and CEO. He was the IEEE Vice President, Technical Activities (2019), Division IX Director of IEEE Board of Directors (during 2016–2017), and the President of IEEE Signal Processing Society (during 2012–2013), in which he also was also the Vice President -Publications (during 2006–2008), and a member on the Board of Governor. He was the Editor-in-Chief of the *IEEE Signal Processing Magazine* (during 2003–2005) and the founding Editor-in-Chief of the *EURASIP Journal on Advances in Signal Processing* (JASP). He was the founder of the Asia-Pacific Association of Signal and Information Processing (APSIPA). He was the Director of Graduate Studies and Research, and Associate Chair of Electrical and Computer Engineering Department.

Dr. Liu was the recipient of two IEEE Technical Field Awards: the 2021 IEEE Fourier Award for Signal Processing with the citation for outstanding leadership in and pioneering contributions to signal processing for wireless sensing and communications, and 2016 IEEE Leon K. Kirchmayer Graduate Teaching Award for exemplary teaching and curriculum development, inspirational mentoring of graduate students, and broad educational impact in signal processing and communications.

He was also the recipient of numerous honors and awards including, IEEE Signal Processing Society 2014 Society Award for influential technical contributions and profound leadership impact (the highest award bestowed by SPS, now called Norbert Wiener Society Award), IEEE Signal Processing Society 2009 Technical Achievement Award (now called Claude Shannon-Harry Nyquist Technical Achievement Award), APSIPA 2018 Grand Award, 1994 National Science Foundation Young Investigator Award, IEEE Signal Processing Society Distinguished Lecturer, more than a dozen of best paper/invention awards, IEEE Signal Processing Society Meritorious Service Award, and EURASIP Meritorious Service Award.

He was recognized by the Web of Science as a Highly Cited Researcher (during 2001–2014 and 2016–2017). He has been a fellow of the AAAS since 2008, and the National Academy of Inventors since 2019. He is honored as 2021 Distinguished Alumni of National Taiwan University. His research was featured as one of seven technologies that IEEE believes will have the world changing implications on the way humans interact with machines, the world and each other, in honor of IEEE's 125th Anniversary.

Dr. Liu and his Origin team invented the world's first centimeter-accuracy indoor positioning and tracking system using the fundamental principle of time reversal, even under non-line-of-sight conditions with only a single commodity Wi-Fi device. His team discovered that due to a large number of multipaths, the time-reversal focusing effect exhibits an energy distribution whose stationary behavior can be harnessed to accurately estimate speed under severe indoor multipaths, a groundbreaking fundamental discovery that broke the impasse of more than 170 years of search for such a solution since the Doppler Effect. With that as the foundation, his Origin team developed a wireless AI platform enabling a wide range of device-free, non-obtrusive sensing technology, including vital signs detection, sleep monitoring events/activities recognition, fall detection, human biometric, and indoor navigation, without any wearables by using commodity ambient Wi-Fi signals.

Dr. Liu was also the founder of Odyssey Technologies in 1997 pioneering the world's first digital surveillance system over Internet. The impact is ever lasting with the ubiquitous uses of cameras for surveillance over Internet nowadays.

He was the recipient of various research and teaching recognitions from the University of Maryland, including Poole and Kent Senior Faculty Teaching Award (2005), Outstanding Faculty Research Award (2008), and Outstanding Service Award (2012), (each with one award per year from the entire college), all from the A. James Clark School of Engineering, Invention of the Year Award (for three times) from the University's Office of Technology Commercialization, and also George Corcoran Award for outstanding contributions to electrical engineering education from Electrical and Computer Engineering Department, and Outstanding Systems Engineering Faculty Award in recognition of outstanding contributions in interdisciplinary research from the Institute for Systems Research.

Dr. Liu was the Prime Architect and Proposer of the IEEE Transactions on Information Forensics and Security, IEEE Journal in Selected Topics of Signal Processing, and IEEE Transactions on Multimedia. He also initiated the creation of the IEEE Transactions on Computational Imaging and IEEE Transactions on Signal and Information Processing over Networks. As the Vice President – Publications, he started the Inside Signal Processing e-Newsletter for IEEE Signal Processing Society. He was the General Chair of 2007 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Hawaii, a Co-General Chair of the First APSIPA Annual Summit and Conference (ASC) in Sapporo in 2009, the Chair of Multimedia Signal Processing Technical Committee, and the Technical Program Chair of 2003 IEEE International Conference on Multimedia and Expo.

He has delivered keynotes/plenaries in various international conferences and workshops and distinguished lectures in many universities/institutes worldwide. He has been a consultant to industry and was also occasionally as an expert consultant/witness for legal proceedings. He was also in the review panels of centers of excellence from various nations and agencies, such as National Science Foundation and European Research Council, and many countries. He was a member of IEEE Fellow Committee.

As a leader in IEEE, he proposed the creation of the IEEE DataPort to offer data repository services to support open science and reproducible research by hosting data that are citable and useful for our community. He also proposed and co-led the development of the IEEE App that serves as Your Global Gateway to IEEE to discover IEEE and network globally.

He is a coauthor of *Reciprocity, Evolution, and Decision Games in Network and Data Science*, Cambridge University Press, 2021, *Wireless AI: Wireless Sensing, Positioning, IoT, and Communications*, Cambridge University Press, 2019, *Behavior Dynamics in Media-Sharing Social Networks*, Cambridge University Press, 2011, *Cognitive Radio Networking and Security – A Game Theoretic View*, Cambridge University Press, 2010, *Cooperative Communications and Networking*, Cambridge University Press, 2009, *Resource Allocation for Wireless Networks: Basics, Techniques, and Applications*, Cambridge University Press, 2008, *Ultra-Wideband Communication Systems: The Multiband OFDM Approach*, Wiley, 2007, *Network-Aware Security for Group Communications*, Springer, 2007, *Multimedia Fingerprinting Forensics for Traitor Tracing*, *EURASIP Book Series on Signal Processing and Communication* (Hindawi), 2005, *Design of Digital Video Coding Systems: A Complete Compressed Domain Approach*, Marcel Dekker, 2001, and a co-editor of *Handbook on Array Processing and Sensor Networks*, IEEE-Wiley, 2009, and *High Performance VLSI Signal Processing: Volume I: System Design and Methodology* and *Volume II: Algorithms, Architectures, and Applications*, IEEE Press, 1998.

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