Towards Liquid Reconfigurable Antenna Arrays for Wireless Communications

Javier Otero Martínez, Javier Rodríguez Rodríguez, Yuanjun Shen, Kin-Fai Tong,
Kai-Kit Wong and Ana García Armada

***Abstract*—Liquid-based antennas promise to overcome crucial limitations of traditional solid-based ones. Here, we describe different liquid antenna technologies that can be used to build arrays with the unprecedented flexibility and adaptivity needed to enable an evolution in wireless communications. We focus on two approaches which use either metallic or non-metallic liquids as radiating elements. In both cases, the resulting devices can be reconfigured dynamically, thus, modifying the radiation parameters of an antenna in real time in an inexpensive way. To that end, we describe some of the challenges that arise when integrating such antennas as part of a whole communication system. We discuss the solutions adopted in some initial prototypes and summarize some of the problems that need to be solved to pave the way for integrating fully reconfigurable liquid antenna arrays in wireless communication systems.**

***Index Terms*—Liquid Antennas, Wireless Communications, Reconfigurable Antennas, eGaIn**

I. INTRODUCTION AND MOTIVATION

ANTENNAS play an important role in present day communication systems: they transmit or receive information according to the specifications which different applications impose. The evolving communication paradigms require the use of a variety of technologies that must coexist within the same device, as it occurs in modern-days cell phones, for example. With the number of possible combinations being overwhelmingly high, current materials and fixed topologies are limited and hinder the much-needed scaling up of the performance at a feasible cost.

Liquid antennas represent an alternative in which the main conductor is a liquid material. They were conceived in 1990s when designers focused on improving flexibility and reconfigurability. Reconfiguration is achieved when antennas reversibly change their geometry, modifying their performance. Such reconfigurability would tune the operating frequency to different bands, offer real time multi-user cancellation or dynamic modification of their coverage area with minimal hardware or computational cost.

Liquids present some advantages compared to solids as antenna radiating elements. For example, they are easily reshapeable, adopting the shape of their container. The irruption of liquid electronics has enough potential to redefine trendy applications such as wearable electronics, implantable biomedical devices, multi-user communications systems and many more [1]. Liquids are useful not only for reconfigurable devices, but also for resisting impacts, strains or deformations that would break other materials.

Moreover, not only antenna hardware is involved when choosing liquid materials, but every other element that is needed in the process of communication. Consequently, whilst most of the reported work on liquid antennas have a perspective on such devices as radiating elements, this article describes the challenges that arise when integrating such antennas as part of a multi-antenna communication system as a whole. Antenna, transceiver, pre/post coding techniques, hardware and other concepts such as spatial multiplexing (See Figure 1) or diversity gain are studied, based on the insights gained with some early prototypes. The aim of this work is to provide an overview of existing works on the field and to offer future perspectives on their expected impact on the evolution of communication systems exploiting liquid antenna array.

There are two main possibilities regarding liquid antenna technologies: non-metallic and metallic materials. Both are described in this article. The former principally uses water with different salt concentrations to get certain conductivity values. Since water is abundant, cheap and easy to handle, its applications in this context are being explored with interest. Other conductive solutions are also feasible, depending on their composition. On the other hand, metallic liquid antennas present much better electrical features while their thermal properties are more convenient for radio-frequency (RF) techniques. Nowadays gallium-based alloys are the choice being explored the most [2]. Either way, each solution is challenging in their own way. The understanding of these materials and their properties is yet scarce and there are no commercial applications developed for liquid metals in this field.

Metallic materials based on gallium, like eutectic indium-gallium (eGaIn) or its alloy with tin (Galinstan), present interesting electrical features while they are not toxic nor flammable, unlike their traditional competitor, mercury. The latter is currently banned precisely for that reason, being rapidly substituted by other materials. The main drawback of these new materials is that they are not easily found in nature hence they must be processed, rising their cost. On the other hand, non-metallic materials are in general much more abundant and can be handled more easily.

The use of liquid antennas to conform arrays makes it possible to obtain directive transmissions using elements that are not as directive. Now, antenna arrays have made possible the implementation of multiple input-multiple output (MIMO) processing. However, fully exploiting MIMO requires a number of hardware electronics which equals the number of elements of the array. That is why state-of-the-art massive MIMO systems [3] present scalability problems. On the contrary, liquid arrays would not need as many of such circuits as the reconfiguration is achieved by modifying their geometry. Then, this technology

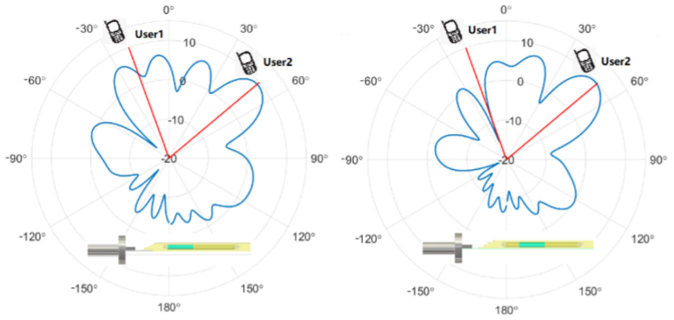


Fig. 1. Pattern diversity of a fluid antenna with the fluid radiator at 0 mm (left) and 3 mm (right) from the reference position at 26 GHz. Source [4]

would be cheaper and may help to reduce the size and energy consumption of wireless communications systems. However, due to the practical limitations that emerge when creating single-element liquid antennas, there is a path that must be cleared before incorporating liquid-based elements into arrays to enable MIMO processing. This article aims to describe such a path towards liquid MIMO communications.

Reconfigurable antennas are conceived to solve these problems by adding a new dimension for adaptation - geometry - that not only expands the possibilities of array technologies, but also may be used to substitute expensive electronic devices. Furthermore, during the last years, a wide variety of communication strategies have emerged, e.g. cognitive radio, enabling the use of different frequency allocations. New generation devices must be able to comply with this trend and operate adequately in these multiple bands, and liquid antennas are also alternative techniques compatible with this novel paradigm.

After this introduction, Section II describes two different approaches using metallic or non-metallic conductors. Along this description, a summary of the different features of such materials is included. Section III shows the problematic that emerges when combining electronic and fluid circuits as well as their interaction. Some feeding techniques are explained in Section IV, as they are particularly relevant for transceivers with liquid antennas. Section V describes some research focused on the enhanced communications performance enabled by arrays of liquid antennas. Finally, two different prototypes are described in Section VI, showing the feasibility of this technology as well as how some of the concepts introduced during the present document are implemented. The article concludes outlining the road ahead towards reconfigurable arrays of liquid antennas.

II. MATERIALS FOR LIQUID ANTENNAS

A. *Non-metallic Liquid Antennas*

Any conductive material can be used - in principle - to build antennas. However, due to its abundance, low cost and easy handling, water has been explored with interest for RF applications. Different salt concentration percentages, from distilled to saturated, conductivity and freezing point of the mixture can be defined, providing an interesting degree of freedom to the design.

Whilst water presents some obvious advantages, its main drawback lies in the dependency of conductivity on both frequency and temperature. Consequently, it is hardly possible to model its behavior in regular non-experimental environments. In addition, some authors [5] suggest the use of other substances to be mixed with water, like ethanol. The latter decreases the freezing point of the solution at the cost of a degradation of antenna efficiency, as it modifies the permittivity and the Electromagnetic (EM) features. Another option [6] is propylene glycol which is largely produced to manufacture different polymers. Presenting low volatility, it is not toxic (it can even be used to sweeten industrial beverages) and prevents freezing - depending on the concentration - up to $-60°C$. Although it also degrades the radiating properties by increasing the relative permittivity, it seems to be more suitable than ethanol or salts.

Other non-water-based substances have also been explored [2]. Some examples are oils, organic solvents and ionic liquids such as mineral oil, acetone and trihexyl-tetradecyl-phosphonium chloride, respectively. In general, this group presents low conductivity compared to water-based compounds and metallic alloys. Nonetheless, they present much better stability when exposed to frequency and temperature changes, which is their main advantage. Furthermore, ionic liquids constitute a novel opportunity for RF technologies as they are not flammable while presenting reconfigurable electric conductivity for large electrochemical windows. They are yet to be deeply studied but they seem to be an excellent alternative.

B. *Metallic Liquid Antennas*

Eutectic Gallium-Indium (EGaIn) is a homogeneous alloy which consists of approximately 25% indium and 75% gallium [1]. This composition corresponds to its eutectic point. That is to say that the freezing point of the result is lower than any other alloy of these two metals. This concept may look counter-intuitive but it is the same principle that suggests adding salt to the sidewalks to prevent ice formation. EGaIn's eutectic point at 15.3°C makes it liquid at room temperature.

Nevertheless, it has some features that make its use challenging. EGaIn rapidly reacts with oxygen creating a passi-

Non-Metallic	ε_r	**Freezing Point (C)**
Water	78	0
Salt Water (5%)	65	-2.5
Water 5% PG	77.5	-3
Water 5% Ethanol	77	-3
Acetone	∼20	-84
T - chloride	∼2	-70
Metallic	**Conductivity (S/m)**	**Freezing Point (C)**
Mercury	10^6	-39
eGain	$3.4 \cdot 10^6$	16
Galinstan	$3.3 \cdot 10^6$	-19

TABLE I
COMPARISON OF DIFFERENT MATERIALS. ALL MEASURES AT ROOM TEMPERATURE. PERMITTIVITY MEASURES AT 1 GHZ. SOURCE: [2]

vating outer layer of oxide [7]. Once the metal has oxidized, its shape remains constant at room temperature, hindering adaptive approaches. To solve this problem, direct contact with air must be avoided using buffer solutions, which can even dissolve such oxide layer after its formation. Nevertheless, this oxidation process can be used to easily print thin metallic circuits. The use of such buffer solutions, like $NaOH$ or HCl, increases the design complexity. In addition, although they present low conductivity values, their influence on the RF circuit must be taken into consideration.

For RF applications, eGaIn emerges as a perfect match for flexible, reconfigurable antennas, improving their efficiency in comparison to non-metallic materials. Galinstan - Gallium-Indium which contains 10% tin -, presents similar features with an even lower melting point of $-18°$C, being even more suitable for a higher number of commercial applications. In addition, their dependency on frequency and temperature is smaller compared to water, hence they are easier to model and more stable. Less common materials - also based on gallium - are used to create conductive inks with controlled viscosity values, but they are not adequate for applications in which reconfigurability is pursued, as they ought to be printed. It is undoubted that thanks to their thermal and electric properties, gallium-based alloys have replaced mercury for antenna applications.

However, the majority of these materials have not been characterized deep enough to overcome the challenges that they present. Further experimentation is needed to fully understand their working principles and their corresponding niche applications.

III. ADAPTIVE STRATEGIES WITH FLUIDS

The consequence of using adaptable liquid technologies is that pumping systems are required to be able to control the flow within the device. Furthermore, design steps must include closed fluid circuits, which must be considered carefully when integrating them with regular communication systems. The design of these systems is challenging for electronic or RF engineers as it requires strong fluid mechanics background to design and implement them.

As a first approach, mechanical means have been used to control liquid antenna circuits. Metallic and non-metallic materials share the same principles. Liquids reshape easily but they cannot be compressed as gasses. This is realized by syringes or pumps to displace the liquid proportionally. Viscosity is the physical property that is defined as the resistance to be deformed by shear. In this case, it defines the power that is necessary to apply in order to displace the fluid, hence to control the performance of a liquid antenna. Mechanical pumping systems are simple to conceive but harder to implement in practical communication applications. Basically, every mobile part is prone to suffering from an eventual degradation, in comparison to those that are fixed. In addition, such a degradation may cause, not only leaks, but a loss of accuracy which would require high maintenance expenses.

Time and size constraints are probably the most limiting factor. Antennas are dependant on their physical dimensions to define their performance. Furthermore, novel communication systems that make use of millimeter wavelength technologies have drastically reduced their size, due to the higher operating frequency. Nowadays, electronic circuits can be extremely small, which is not always easily achievable with traditional technologies. Microfluidics is the name of the field that studies fluids in small scale. Concretely, pumps are one of the most important components. For fluid communication systems to perform as intended, reconfiguration time must be characterized as it would define their specifications and the feasibility of their applications. Our current designs, which are based on mechanical pumping systems, present a reconfiguration time in the order of hundreds of milliseconds (∼100ms). To reduce the reconfiguration time, it is necessary to develop adequate pumping techniques within the next years. Pumps should be able to operate faster and handle smaller flows with precision while reducing its price. Fortunately, it can be seen that this topic has become trendy, being the object of multidisciplinary research for communications, fluid mechanics and bio-engineering to cite a few examples. In addition to mechanical pumps, other pumping techniques shall be explored in parallel as well, improving their possibilities and their feasible applications.

A. Electrochemically Controlled Capillarity

Since mechanical means present several limitations that must be overcome for practical applications, Electrochemically Controlled Capillarity (ECC) emerges as a feasible alternative. Such technique consists in exposing conductive liquids to electric fields [8]. Electric fields can modify the rheological, surface and wetting properties of conductive liquids - like eGaIn - varying parameters such as surface tension or viscosity. Surface tension is a parameter that represents how resistive the liquid is when trying to increment its surface, having many implications. Wetting is one of the effects of this property: the higher the surface tension, the harder for that liquid to wet other substances. In ECC, the wettability is modified when the electric field is applied, resulting in a variation in the geometry of the liquid. Figure 2 shows how a metallic droplet is displaced using this technique. Such changes require higher voltage values when applied to other materials not as conductive as metals, which in the end limits the applicability of such materials.

ECC is meant to substitute mechanical pumping systems, eliminating mobile parts and using less space in comparison with a pump, as a single electrode should always be smaller than a device. However, it also presents some limitations. For non-metallic solutions, which are commonly ionized water or electrolytes, electrolysis appears when exposed to electric currents. That is a phenomenon that can drive a flow, but it also changes the gradient of concentration of the solution, produces bubbles and degrades the electrodes, according to our preliminary tests. Besides that, the most limiting factor to apply ECC is the lack of a deep characterization that is needed to implement such a technique. One would like to find a table relating the voltage with the flow rate, or something similar. However, experiments usually address a particular setup instead of a general application. This is one of the topics being under the scope of our current research.

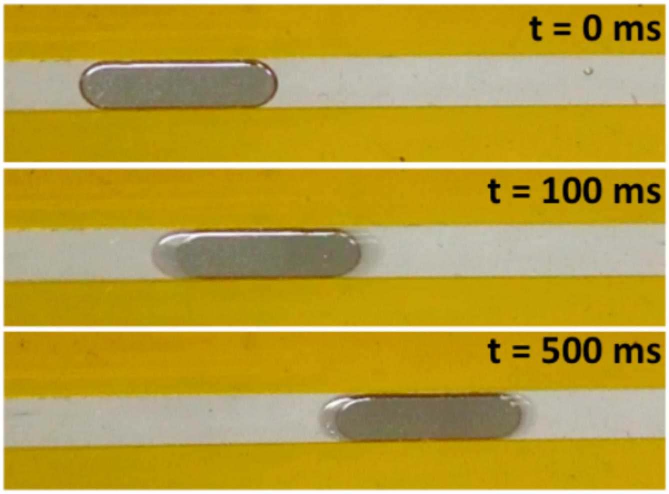


Fig. 2. ECC experimental demonstration. Source [8]

However, there is an interesting synergy when combining ECC with liquid metals. Since the conductivity of a metal is much better than the one presented by the buffer solution at which it is submerged, the alloy is much more sensitive to current gradients. Therefore, a drop of eGaIn that is confined by a tube, for example, can be remotely displaced using low pulses which would not produce electrolysis. In consequence, a column of eGaIn can be displaced, modifying the radiation parameters of an antenna that uses it as conductor. In fact, we have performed some preliminary experiments which showed that with only 100 mV, a droplet of eGaIn would travel throughout a thin capillary steadily, without creating any bubble. Hence, an additional Direct Current (DC) circuit would need to generate the signal to control the position of the metal. The two resulting stages would generate and combine the signal to feed the antenna.

In terms of scalability, current MIMO systems require a number of electronic circuits that grow directly proportional to the number of elements of the array. Such circuits, often referred to as 'RF chains' include several components like phase shifters and isolators. These two are often expensive and, moreover, need to be addressed as an essential part of the radiation. A minimal mismatch in one of the elements can propagate to the shape of the radiation pattern of the whole array. On the other hand, a successful application of ECC to liquid antenna arrays would reduce both complexity and cost, as the number of RF chains would be substituted by more efficient fluid circuits to control such radiation properties. A simulation example of a reconfigurable antenna controlled by voltage can be found in [9].

IV. FEEDING TECHNIQUES

One of the most delicate parts of the design of liquid antennas is the contact between the liquid conductor and the rigid RF parts: connectors, microstrip lines, components, etc. In general, liquids guarantee perfect contact when wetting a metallic plate. That is the principle behind tin welding. As long as the two substances do not chemically interact with each other, a good current transfer is achieved.

There are many examples in the literature of antennas designed using this direct contact approach, as it is the simplest [10]. Whereas perfect contact may be enough for the majority of applications, it mat not be the best choice for its use with reconfigurable antennas.

Modifications in the shape or in the amount of conductor within the antenna fluid circuit change the input impedance. As the liquid flows, the impedance mismatch with respect to the feeding transmission line also varies. In consequence, such antenna could only be used within the limited frequency range in which the input matching network can compensate that variation of the input impedance, in order not to create a significant standing wave at the feeding point. The impedance mismatch at the feeding point will reflect the income signal propagating into the antenna, therefore highly degrading the antenna efficiency. Hence, since one of the main purposes of developing liquid antennas is achieving frequency reconfiguration, it is not acceptable to be limited by the performance of an input matching network.

Alternatively, there are techniques that do not necessarily require direct contact between the liquid conductor and electrodes. A wise use of coupling effects would allow us to feed antennas while isolating the liquid material [11], as illustrated in Figure 3. In this work, the authors feed a saline water monopole using a coupling ring. On the other hand, these approximations rely on a clean environment in terms of electromagnetics, as any external field would affect the performance of the whole system.

Another solution consists of placing such liquid materials near the antenna, to be used as reflectors or parasitic elements. These reflections conform the final shape of the radiation pattern without influencing the input impedance, as they are not in contact with the conductor, Fortunately, coupling techniques are already developed with multiple approximations. The one presented in [12] is summarized below in Section VII.B.

Feeding techniques are something critical when designing an antenna array. It is important for all the elements to radiate

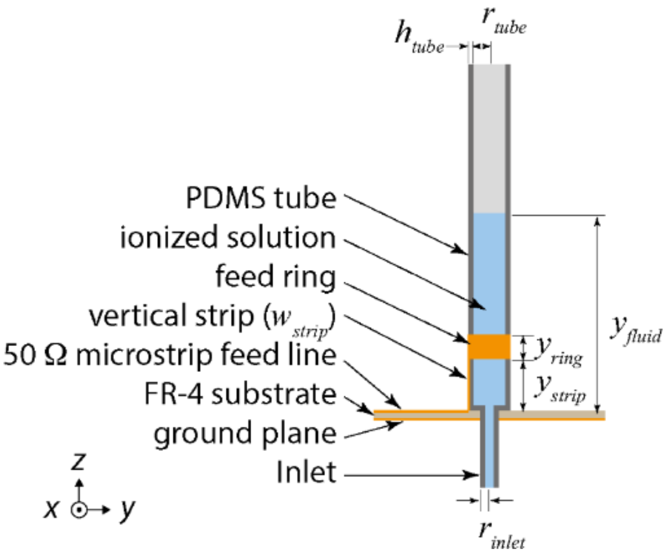


Fig. 3. Coupling feeding antenna prototype.

just as they are expected to, which in this end is achieved by their feeding networks. Note that, if using coupling techniques in aggregation with ECC, only one network per element would be necessary to both shape the liquid and supply the RF signal for radiation purposes. This would minimize the number of electronics necessary to build the array.

V. LIQUID ANTENNA AIDED MIMO COMMUNICATION SYSTEMS

While the radiation properties of a liquid antenna are essential in dictating the fundamental transmission/reception performance for wireless communications, the reconfigurability of liquid antennas within the communication system as a whole, is as important. Liquid-based materials enable software-controlled position-tuneable antennas to be realized, according to the techniques that were mentioned before. Liquid antennas enable the receiver to browse through the fading envelopes to find the position where this fading envelope is most desirable for communications. Formally, the benefits of a fluid antenna for the system can be characterized by its diversity order and multiplexing gain, like in a conventional MIMO antenna system. The outage probability for a point-to-point communication system using a fluid antenna at the receiver was studied in [4] and it was reported that it was able to match or even exceed a maximum ratio combining (MRC) system with many uncorrelated antennas if the resolution for switching its position, quantified by the number of ports, is sufficiently large.

The work [13] further proposed to use a liquid antenna for multiple access. This is made possible because the fluid radiating element can be switched to a position at which the interference suffers from a deep fade and thus vanishes naturally. This work demonstrated that under ideal conditions, liquid antenna aided communication systems could support hundreds of users on the same radio channel without precoding nor sophisticated resource allocation.

This work is offering a theoretical support to the idea of yet another possibility for reconfiguration. Instead of managing each element in a separated way, the geometrical reconfiguration could be implemented by putting (or not) in contact the liquid with several ports placed on different positions inside a larger deposit. This contact would activate such ports varying the resulting radiation pattern. By doing so, a unique fluid circuit would be necessary to control every radiating element of the array, with all the advantages that it offers. The promising performance of fluid MIMO systems relies on having a large number of ports, or a sufficient resolution in space to identify the unexplored opportunities for desirable signal reception.

VI. EARLY PROTOTYPES

A. Metallic conductor

The team of Universidad Carlos III of Madrid has developed a monopole prototype using eGaIn as liquid conductor. It consists of a glass capillary that is directly sunk into a conic deposit which contains eGaIn. The other edge of the capillary is connected to a syringe, used to deliver the metal, changing the physical height of the resulting monopole. The fluid circuit is filled with a 1M buffer solution of $NaOH$.

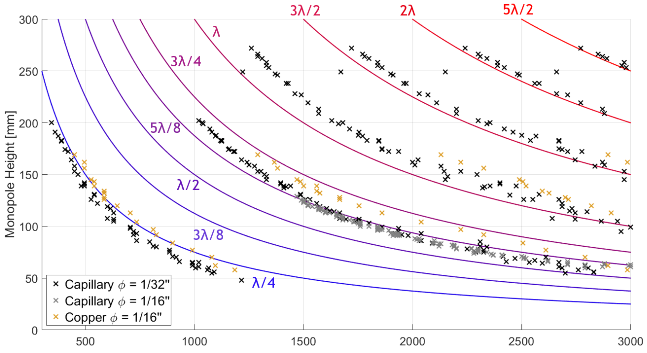


Fig. 4. Resonant frequency of the monopole for different eGaIn heights. Blue curve represents the ideal height-frequency ration for a $\lambda/4$ monopole.

The experimental results of this monopole prototype show that it can vary its resonant frequency from 0.5 to 3 GHz, covering several bands of interest for wireless communications. With minimum refinements, it is expected to work up to 5 GHz, to cover the lower frequencies of 5G.

The reflection coefficient (S_{11}) has been measured for different monopole heights using a Vector Network Analyzer (8714ET-Hewlett Packard). Measured values can be found in Figure 4, where the variation of the resonant frequency can be seen along with the metal height.

In addition to the frequency at which the antenna resonates, the blue curve corresponds to the direct height-frequency relation for quarter-wavelength, $\lambda/4$, monopoles. Subsequent curves, turning to red, compare the height with different wavelengths. Whilst experiments with two different capillary widths have been performed, a copper rod was also included as reference. No differences were observed experimentally when comparing copper and eGaIn as antenna conductors. The slight mismatch between theoretical and experimental values may be due to prototype manufacturing, leaks, connector insertion loss, etc. Such mismatch is, nontheless, linear hence easy to compensate. In addition, it is observed with copper also, therefore it is reasonable to assume that it has to do with prototype manufacturing, not with the properties of any anomalous behavior of eGaIn.

This experimental setup demonstrates that eGaIn is suitable for adaptive antenna applications, since it behaves as predicted. Other works such as [14] place several liquid monopoles in a row to build more directive radiation patterns.

B. Metallic reflector

A completely different approach is used by the team of University College London (UCL). It consists in a surface-wave based fluid antenna system, which is shown in Figure 5. The surface wave launcher excites a surface wave propagating towards the fluid radiator located inside the fluid channel in the container on a microwave substrate. When the surface wave arrives at such radiator, the wave will be scattered into free space. As the fluid radiator can be shifted along the fluid channel using either a nano-pump or electrowetting, the

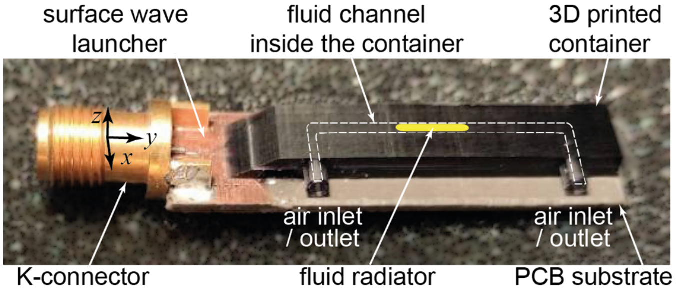


Fig. 5. Prototype manufactured by UCL, containing the geometry of the surface wave-based fluid antenna.

scattering of surface wave can take place at different positions along the fluid channel and therefore spatial diversity can be achieved. The surface wave-based design is also motivated by its wideband characteristics. S_{11} measures indicate that the fractional bandwidth ($|S_{11}| < -10$dB) of the antenna is about 49%, which can cover 23 to 38 GHz, being suitable for the 5G millimeter wave band.

Additionally, the surface wave-based fluid antenna has an interesting property. It provides pattern diversity, as shown by the full EM simulation results in Figure 1. The results illustrate that as the fluid radiator changes its position over the fluid channel, the radiation pattern changes. In particular, the situation is that the interference (User1) comes from the direction of about -20° which should be eliminated. Such figure shows that if the fluid radiator's position is switched to 3 mm from the reference position, then the pattern will have a null at -20°, effectively nullifying the interference. Such pattern diversity has great potential to handle multiuser interference when scattering is limited in the environment. More research, however, is needed to understand the relationship between the pattern and the radiator's position as well as the degrees of freedom. On the other hand, if the environment has many scattering obstacles, the channel will be more dispersive and spatial diversity will be more relevant. It will be of great interest to see if the surface wave-based fluid antenna design in Figure 5 can be adapted to handle this case.

VII. THE ROAD AHEAD TOWARDS LIQUID ARRAYS

The technology exemplified in the early prototypes needs to be refined to be able to manufacture commercial liquid antenna array systems in the future. As it was stated, liquid antenna technologies require more specific research effort to achieve sufficient isolation when combined in an array. By the same token, novel feeding methods are needed to optimise the antenna wideband performance, for every different location of the liquid elements within an array.

For that purpose, novel fluid pumping methods are required. Either refined versions of mechanical means, alternatives like the one we are studying, ECC, or a combination of both. Its influence on the performance of the arrays is also yet to be tested as the design of such components is challenging. Rheological properties of the liquid materials must be characterised in experiments, where the material is manipulated in low-complexity, controlled flow configurations. The outcome would allow to apply computational fluid dynamics (CFD) to model the flow of liquid within the generally narrow, small circuits.

Liquid antenna diversity techniques are already proposed but there is almost none experimental data to support analytical assumptions about creating arrays with them. Furthermore, such diversity techniques rely till now on the quick displacement of a liquid within its container, rather than the separate feeding of every element of the array that would be required for MIMO operations. On the other hand, a developed liquid antenna array system has the potential to take advantage of diversity and spatial multiplexing like no other technology, opening new directions for the design and optimization of modern systems that were not considered possible before. The fluid antenna array, a system with multiple liquid-based antenna elements, presumably can offer higher potential to revolutionize wireless communications.

It is necessary to note that many of the practical limitations of single element liquid antennas such as pumping or feeding are critical when expanding them to an array configuration. This is not a limitation but an opportunity for us, as designers, to conform systems that improve our current communication technologies. Some of the challenges that emerge are related with the mechanical response to transients, stability against vibrations, impacts or mechanical demands and energy consumption. To answer these questions, further experimentation and characterization would be - and is being - carried out by several working teams within the next few years.

REFERENCES

[1] M. D. Dickey, *Emerging Applications of Liquid Metals Featuring Surface Oxides*, ACS Appl. Mater. Interfaces, vol. 6, n.º 21, pp. 18369-18379, nov. 2014, doi: 10.1021/am5043017.

[2] Y. Huang, L. Xing, C. Song, S. Wang and F. Elhouni, *Liquid Antennas: Past, Present and Future*, IEEE Open J. Antennas Propag., vol. 2, pp. 473-487, 2021, doi: 10.1109/OJAP.2021.3069325.

[3] A. Shojaeifard et al., *MIMO Evolution Beyond 5G Through Reconfigurable Intelligent Surfaces and Fluid Antenna Systems*, Proc. IEEE, pp. 1–22, 2022, doi: 10.1109/JPROC.2022.3170247.

[4] Y.Shen, K. -F. Tong and K. -K. Wong, *Beam-steering Surface Wave Fluid Antennas for MIMO Applications*, 2020 IEEE Asia-Pacific Microwave Conference (APMC). pp. 634-636, doi: 10.1109/APMC47863.2020.9331647.

[5] L. Xing, Y. Huang, Q. Xu, S. Alja'afreh and T. Liu, *Complex Permittivity of Water-Based Liquids for Liquid Antennas*, in IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 1626-1629, 2016, doi: 10.1109/LAWP.2016.2519542.

[6] E. Motovilova and S. Y. Huang, "*¿A Review on Reconfigurable Liquid Dielectric Antennas,* Materials, vol. 13, no. 8, p. 1863, Apr. 2020, doi: 10.3390/ma13081863.

[7] Q. Xu, N. Oudalov, Q. Guo, H. M. Jaeger and E. Brown, *Effect of oxidation on the mechanical properties of liquid gallium and eutectic gallium-indium*, Physics of Fluids, vol. 24, n.º 6, p. 063101, jun. 2012, doi: 10.1063/1.4724313.

[8] R. C. Gough, A. M. Morishita, J. H. Dang, W. Hu, W. A. Shiroma and A. T. Ohta, *Continuous Electrowetting of Non-toxic Liquid Metal for RF Applications*, IEEE Access, vol. 2, pp. 874-882, 2014, doi: 10.1109/ACCESS.2014.2350531.

[9] F. Xie y M. S. Tong, *A Novel Reconfigurable Liquid Metal Antenna Controlled by an Impressed Voltage*, en 2018 Progress in Electromagnetics Research Symposium (PIERS-Toyama), Toyama, ago. 2018, pp. 2314-2317. doi: 10.23919/PIERS.2018.8598010.

[10] F. Xie, J. J. Adams and M. S. Tong, *An UHF Reconfigurable Liquid-Metal Monopole Antenna Based on a Two-Dimensional Surface*, p. 8.

[11] C. Borda-Fortuny, L. Cai, K. F. Tong and K.-K. Wong, *Low-Cost 3D-Printed Coupling-Fed Frequency Agile Fluidic Monopole Antenna System*, IEEE Access, vol. 7, pp. 95058-95064, 2019, doi: 10.1109/ACCESS.2019.2928683.

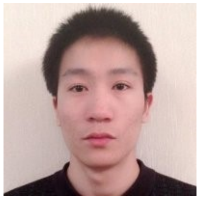
[12] M. I. Nawaz, Z. Huiling, M. S. Sultan Nawaz, K. Zakim, S. Zamin and A. Khan, *A review on wideband microstrip patch antenna design techniques*, en 2013 International Conference on Aerospace Science & Engineering (ICASE), Islamabad, Pakistan, ago. 2013, pp. 1-8. doi: 10.1109/ICASE.2013.6785554.

[13] K.-K. Wong and K.-F. Tong, *Fluid Antenna Multiple Access*, IEEE Trans. Wireless Commun., pp. 1-1, 2021, doi: 10.1109/TWC.2021.3133410.

[14] A. M. Morishita, C. K. Y. Kitamura, A. T. Ohta, y W. A. Shiroma, *A Liquid-Metal Monopole Array With Tunable Frequency, Gain, and Beam Steering*, Antennas Wirel. Propag. Lett., vol. 12, pp. 1388-1391, 2013, doi: 10.1109/LAWP.2013.2286544.

JAVIER OTERO MARTINEZ received the B.Sc. in Telecommunications Engineering in 2019 from the Universidad Politécnica de Madrid and two M.Sc. corresponding to Telecommunications Engineering and Advanced Communications Technologies from the Universidad Carlos III de Madrid in 2021. There, he is currently pursuing his PhD within the Department of Signal Theory and Communications. Some of his current research interests are liquid antennas, array, communication technologies and their testing and measurement acquisition.

JAVIER RODRÍGUEZ RODRÍGUEZ received his degree in Aerospace Engineering at the School of Aeronautics of the Polytechnic University of Madrid in 2000. After that he moved as a teaching assistant to Carlos III University, where he got his PhD in Fluid Mechanics in 2004 under the supervision of Prof. Carlos Martínez-Bazán. His thesis research concerned the breakup of gas bubbles in a turbulent jet. In 2005 he moved to the University of California at San Diego as a postdoctoral researcher in the team of Prof. Juan C. Lasheras, where he worked in cell mechanics and wave dynamics. In 2012 he completed his degree in Physics at UNED. Since 2006 he is part of the Fluid Mechanics Group of Carlos III University of Madrid, where he works on bubble dynamics, buoyancy-driven flows, microfluidic flows and biofluid mechanics.



YUANJUN SHEN (Graduate Student Member'19, IEEE) received the B.Eng. degree from Tianjin University, China, in 2014, and the M.Phil. degree (Distinction) from King's College London UK, in 2016. Currently He is a a full-time research assistant in UCL, working on IoT and low power long range meshed wireless sensor network, meanwhile he is studying part-time PhD in fluid antenna design at millimeter wave for mobile communications.

KIN-FAI TONG (M'99-SM'13, IEEE) is a Professor of Antennas and Applied Electromagnetics at University College London, UK. Dr. Tong is also a Fellow of the Electromagnetics Academy (MIT, USA). He was the General Chair of the IEEE iWEM 2017. He is a Chartered Engineer in the UK. His current research interests include millimeter-wave antennas, fluid antennas, 3D printed antennas, and the sub-GHz long-range IoT networks.

KAI-KIT WONG (M'01-SM'08-F'16) received the BEng, the MPhil, and the PhD degrees, all in Electrical and Electronic Engineering, from the Hong Kong University of Science and Technology, Hong Kong, in 1996, 1998, and 2001, respectively. He is Chair in Wireless Communications at the Department of Electronic and Electrical Engineering, University College London, UK. His current research centers around 6G mobile communications. He is Fellow of IEEE and IET and is the Editor-in-Chief for IEEE Wireless Communications Letters since 2020.

ANA GARCÍA ARMADA is a Professor at Universidad Carlos III de Madrid. She has been a visiting scholar at Stanford University, Bell Labs, and University of Southampton. She has published more than 200 papers in conferences and journals and she holds five patents. She serves on the editorial boards of IEEE Transactions on Communications, IEEE Open Journal of the Communications Society and ITU Journal on Future and Evolving Technologies. She has been a member of the organizing committee of several conferences. She has received several awards from UC3M, the third place Bell Labs Prize 2014, the outstanding service award from the IEEE ComSoc Signal Processing and Communications Electronics technical committee and the outstanding service award from the IEEE ComSoc Women in Communications Engineering standing committee. Her research mainly focuses on signal processing applied to wireless communications.