Fluid Antenna System for 6G: When Bruce Lee Inspires Wireless Communications

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Abstract

Since its inception, multiple-input multiple-output (MIMO) has become a magical technology that continues to break new grounds and deliver the needed upgrades in mobile communications. The emerging 5G systems are also being labelled by many as the massive MIMO generation. This somewhat oversimplified view is perhaps a reflection of the great impact MIMO has had on our generation of mobile communication networks. Although the technologies have evolved in the past decades, the principle remains the same–to exploit the diversity of different copies of signals at independent locations for reducing the degree of fading and randomness of wireless channels. Through signal processing and coding, the diversity has been translated successfully into capacity gain and enhancement in other forms of the quality-of-service. This article identifies "fluid" antenna as a trending technology that may succeed MIMO and become a reality to transform wireless communications to a new height. Fluid antenna is a radical approach that advocates software-controlled position-flexible shape-flexible antenna. The concept liberates antennas to unleash massive diversity inherent in the small space of a mobile device and makes possible new opportunities that were previously unthinkable. This article attempts to be imaginative and aims to take readers on a short journey of what fluid antenna might bring in future-generation mobile communications systems and speculate on its impact.

Introduction

"*Be formless … shapeless like water … now you put water into a cup, it becomes the cup … you put water into a bottle, it becomes the bottle … put it in a teapot, it becomes the teapot … water can flow … water can crash … be water, my friend*."

These were the lines written and recited by Bruce Lee, the arguably most influential martial artist of all time, in the TV series *Longstreet* back in 1971. This philosophy has inspired many martial artists and is at the heart of Jeet Kune Do, the martial arts system Lee founded in 1967. Some parallels can be drawn to applications beyond martial arts, such as wireless communications, which is what this article is about.

Cabled communication, despite its high capacity, is rigid and inflexible. Wireless communications by contrast give the convenience of ubiquitous communication without the physical restrictions, which has completely transformed the way people live and interact with the world. However, providing certainty in performance from an uncertain medium is the fundamental problem for wireless communications. Randomness due to channel fading and unpredictable interference makes it uniquely challenging.

Wireless communication technologies are all about adaptation and agility to deal with dynamic and hard-to-predict radio environments. Dynamic frequency allocation, adaptive power control and modulation, and smart scheduling are among the many examples of adaptation we can find in today's mobile communications networks. Of particular importance is multiple-input multiple-output (MIMO), which is one of the greatest advances in mobile communications over recent decades. In MIMO, multiple antennas are deployed far apart at fixed locations at both the transmitter and receiver sides and the independent fading experienced by different antenna pairs helps reduce the instability of a wireless channel (the well-known channel hardening effect).

The impact of MIMO in mobile communications has been instrumental, from Alamouti coding and BLAST in 3G to multiuser MIMO in 4G, to the latest massive MIMO in 5G. While the number of antennas at a base station has been drastically increased to 64 or more in 5G, the number of antennas in user equipment (UE), such as handsets, remains surprisingly small. This is due to the limited space at the UE, as the common practice is to deploy multiple antennas only if they are sufficiently apart (≥ half of the wavelength) to ensure diversity of signals.

Although the rule of thumb regarding antenna separation at the UE appears logical and sensible, it makes us wonder if it is possible to utilise the spatial diversity in a small space of UE more effectively. What if an antenna can be formless, shapeless like water? This is the inspiration that can be taken from Bruce Lee's philosophy to innovate antenna design–seeking a new form of antenna that offers new opportunities and avenues for research. Indeed, if antenna can be formless or shapeless, then its reconfigurability and agility will be exceptional. In the rest of this article, we share our imagination for such fluid-like antenna and review some literature that suggests formless shapeless fluid antenna may not be a dream but is as real as any other emerging technology that may impact the development of 6G systems [1].

What is fluid antenna?

The term "fluid antenna" was first used in [2] when distilled water and chemicals were studied as potential materials for an antenna, but reconfigurable fluid antennas emerged only in recent years. There has been an upsurge of research for liquid-based antennas using liquid metals or ionised solutions for various reconfigurability, e.g., [3]–[5]. They all fall into the category of this new form of antennas.

Fluid antenna may represent any antennas equipped with software-controllable fluidic structure, and which can alter their shape and position to reconfigure the polarisation, operating frequency, radiation pattern and other antenna performance metrics, and it may include designs involving no fluidic materials if they can mimic the agility. Fig. 1 illustrates the concept of a possible realisation on a handset where conductive fluid is installed on a tube-like structure within which the fluid is free to move. In this design example, the shape of the antenna cannot be changed but its position can, which may be exploited for diversity and capacity benefits [6].

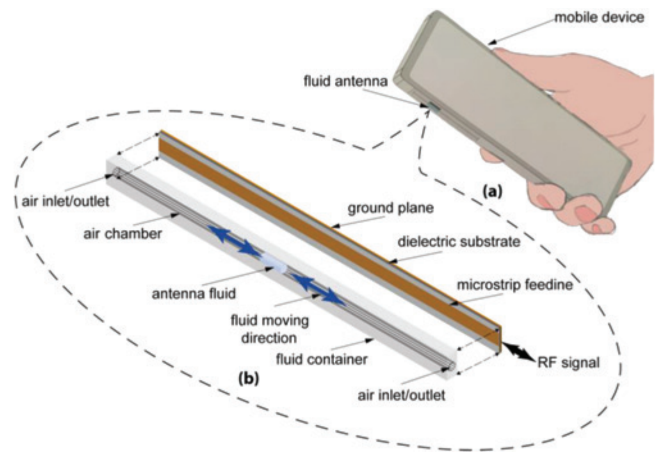

Fig. 1 *A potential geometry of a fluid antenna on smartphone. (a) Smartphone in hand, and (b) the magnified disassembly diagram of a possible fluid antenna system*

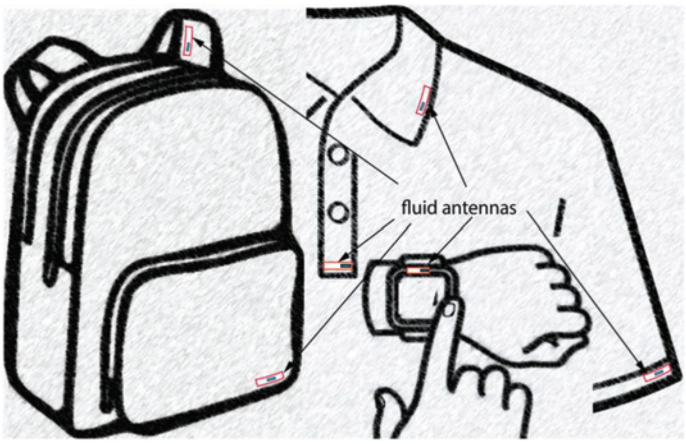

Fig. 2 *A fluid antenna avoiding user's body for efficient radiation*

Conventional antennas have a predefined metallic or dielectric shape for radiation, and therefore have very limited agility. The change to a truly proactive and dynamic integrated antenna hardware architecture is long overdue. There are signs to indicate that the time has finally come for this new paradigm of adaptive fluid-type antennas. As fluid, either metallic, e.g. Eutectic Gallium-Indium (EGaIn), or dielectric, e.g. water and seawater, has no pre-defined shape, consequently, antennas made of fluid in theory can be shaped to any desirable form to adapt to and suit the dynamic wireless environment.

It is worth noting that seawater, albeit much less conductive than metal, has been demonstrated a radiation efficiency of 70% by Mitsubishi Electric [7], and a research group from Nanjing University of Aeronautics and Astronautics in China have even developed an advanced saltwater-based antenna to achieve 360-degree beam-steering that works for frequencies between 334 to 488 MHz [8, 9].

A very rich literature exists for liquid-metal based antennas, see [3]. Fluid antennas using conductive fluids or liquid metals for different reconfigurabilities have also been actively researched in recent years, e.g., [4, 5, 10–12]. There is also an interesting idea to use pixel-like electronic switches for designing reconfigurable antennas and such an idea could be an alternative version of "fluid" antenna [13].

Fig. 3 *Fluid antennas on textiles and wearable equipment*

Opportunities and possible applications

There are opportunities and applications which may benefit from the emergence of fluid antennas.

Fluid antenna can:

- Reduce electromagnetic field exposure and avoid near-field intervention. By adapting its shape, position and radiation pattern, the radiation from a handset can be directed away from the user's head for safety. In the same way, the near-field intervention by the proximity to the user's body can be rectified by the mobility of a fluid antenna. As shown in Fig. 2, a fluid antenna can be mobilised to avoid the user handling of the phone for more energy-efficient radiation.
- Have a very flexible, foldable shape that can be attached to clothes, as illustrated in Fig. 3. The foldable fluid antenna makes it particularly suitable for wearable devices.
- Provide theoretically *unlimited* diversity if the antenna fluid can move continuously (with infinite resolution) inside the given space [14]. In practice, however, there will always be a finite limit on the number of positions that the antenna fluid can be switched to, but a high resolution on the positions means that exceptionally high reception quality can be obtained in a tiny space.
- Provide extraordinary interference immunity for multiuser communications [15]. By skimming through the fading envelopes observed in the space of the fluid antenna, a fluid antenna can be tuned to operate at the most favourable position where the interference is in a deep fade for reliable communication without the need of complex signal processing for interference elimination.

Fluid antenna takes advantage of spatial diversity as in MIMO but the received signal is taken from the best out of an extremely large number of antenna positions within a given space. Correlation of the positions is inevitable, but its impact is secondary as long as the number of switchable positions is large. Compared to MIMO, fluid antenna achieves the interference immunity through an extreme resolution of fading envelope and avoids the need for advanced signal processing that is normally required in MIMO antenna systems. In addition, note that for conventional MIMO systems, sufficient space is needed to ensure that the fixed antennas are sufficiently apart. That is why in 5G, massive MIMO only appears at the base station but not the mobile devices.

Massive machine type communication (mMTC) is a new service category for 5G to support extremely high connection density. Providing such massive connec-tivity within a limited spectrum normally requires sophisticated coordination among the mobile devices and a great deal of signal processing and resource allocation. The opportunity fluid antenna can bring in this application is the possibility of decoupling the mMTC problem into individual devices' optimisation of their fluid antennas, thereby eliminating the need for device coordination completely and permitting the devices to share the spectrum.

The simplicity in signal processing also makes it a particularly attractive proposal for lightweight inter-net-of-thing (IoT) devices. Smart cities and smart homes will be empowered by the web of information from an astronomical number of IoT devices; yet IoT devices vary in their signal processing capability, intelligence, hardware and battery life. It is therefore very hard to have a single communication standard that can work for a wide range of IoT devices and let them talk to each other reliably and efficiently. The way fluid antenna delivers extraordinary performance at a device is simple and does not depend on the capability of coexisting devices. The achievable performance of an IoT device is determined mainly by the spatial reso-lution of its fluid antenna, and the number of coexisting devices does not affect adversely the performance. In fact, the more the number of simultaneous communications, the deeper the fade the aggregate interference suffers.

As a by-product, information security under the vision of fluid-antenna based wireless communications may be a lot higher, as a large number of multiuser signals overlap or jam all the time, making it unrecognisable to eavesdroppers.

On the other hand, being foldable or bendable makes it possible to deploy a large number of antennas on clothes. Presumably, it would be possible to increase the aperture for capturing the radio signals via the many antennas on clothes and redirecting the signals to the UE for superior reception performance. This may eventually make massive MIMO possible to be deployed at the UE's side.

Apart from the above, there are many other appli-cations that are yet to be explored. More applications will emerge as the fluid antenna technology matures.

Challenges

Fluid antenna research is still at an early stage, although the ideas of using liquid based antennas have been researched for over a decade, and the performance limits under idealised conditions have also recently been studied in [6, 14, 15]. There are major obstacles that still need to be overcome satisfactorily, should fluid antenna play a key role in 6G. From choosing the right liquid for the fluid antenna material to designing an architecture that allows a high spatial resolution of switchable positions, to reducing the response time for switching, etc., there appears to be a long road ahead of us. Besides the implementation challenges, estimation algorithms for capturing the fading envelopes in a nearly continuous space need to be sought as well. It is also of interest to explore the benefits, if any, for having more than one antenna fluid on a device, and how to optimise the signal processing for greater performance. The research opportunities are many, and it will require collective efforts from around the world.

Conclusion

Fluid antenna systems may be interpreted as a direct application of Bruce Lee's combat philosophy on wireless communications. The never-before-seen agility that fluid antenna possesses shows great potential to revolutionise the antenna industry and take mobile communication technology to a new height. Nevertheless, it remains to be seen if fluid antenna will be ready to thrive in 6G. Thus far, the signs are very positive. It is hoped that this article will serve as a catalyst to spark an interest in the research and development on fluid antenna technologies.

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