WHITE PAPER

AMBIENT COMPUTING

A deep dive into ambient computing, possible future ambient experiences and research projects to realise the vision.

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ABSTRACT

Ambient computing experiences occur when humans interact with technology and devices in the real world that are largely invisible, only becoming obvious when needed. Arm experts and leading academics discuss ambient computing in detail, exploring the enormous potential and opportunities from ambient computing, and highlighting the core technology challenges and areas that must be addressed to make future ambient experiences a reality. The joint "ambient agreement" outlines possible future work that could help solve the technology challenges associated with ambient computing.

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What is Ambient Computing?

'Ambient' describes computing experiences where the human real-world interaction with technology and devices becomes largely invisible, only coming to the fore when needed. The billions of devices worldwide across IoT and consumer technology are driving this, but today they still require a wide range of continuous interactions that make them not yet truly ambient. Ambient computing experiences are automatic and proactive, based on the perceived needs and preferences of the user, and happen seamlessly throughout people's daily lives across many different environments. As such, ambient computing has much in common with related fields such as ubiquitous computing, calm computing, and pervasive computing.

To dive deeper into ambient computing and identify key future experiences, Arm experts and a group of leading academics in various fields of technology and human-computer interaction met to discuss and explore ambient computing in more detail. The workshop not only discussed the enormous potential and opportunities arising from ambient computing, but also outlined the core technology challenges and areas that must be addressed to make future ambient experiences a reality.

Jointly, we have formulated the "ambient computing agreement" to be signed by the academics who were in attendance, with a view to working together in the future to further define and solve the technology challenges associated with ambient computing.

Key Characteristics of Ambient Computing

We start from the assumption that ambient experiences have the following characteristics:

- Real-world (e.g. not immersive experiences, or fictional worlds that people may experience from virtual reality (VR)
- User-centric and personalized
- Contextual
- Running in the background "ambiently"

These four areas bring together services, data, and intelligence 'at the edge' with learned behavior to enable the ambient computing agreement of tomorrow. This is made possible through the acceleration of pervasive AI-based technologies across IoT and consumer tech markets, and some of the foundations for ambient computing experiences are already in place today.

Ambient Computing Foundations Today

Smartphones are central to ambient experiences, now and in the future. AI-powered digital assistants on today's smartphones collate user data, sensor data, and data from the ambient workloads, and then present information that is relevant to the end-user. This will advance further to bring more intelligence to the experience, with future digital assistants delivering proactive, personalized, and autonomous experiences with minimal levels of interaction with the user. For example, consumers will expect devices to act on their behalf for a range of pre-defined tasks, or by autonomously identifying mundane tasks where the device could make more efficient use of time.

Wearable devices, like smartwatches, smart rings, and fitness trackers, are other well-known examples of emerging ambient devices. Currently, they collect data from the user and then provide personalized health and fitness recommendations either through the wearable device or on the smartphone. In the future, they will be a key data source for ambient computing systems, and an end point for delivering ambient experiences to the user.

The home, or 'smart home,' is a key area central to ambient computing. This is not just a residential environment, but could include care homes, long-term hotels or apartments, and other locations that people call 'home.' Smart-home devices are available today, such as intelligent lighting systems and thermostats, that require users to input their own preferences manually. However, in the future, we will see these devices provide ambient experiences that can be learned from the user, tailored, and then applied automatically—or a combination of devices all automatically working together with one device activating another through greater interoperability.

There are also examples of ambient computing applications in urban environments. 'Smart cities' use connected infrastructure, like traffic lights, smart signage, and public transportation that adapt to real-time conditions and provide relevant information to the public.

However, these current examples beg the question – what is the future for ambient computing? What will be the key opportunities and use cases for ambient computing's future? And what will be the main obstacles and challenges to making advanced ambient experiences a reality and a common part of our daily lives? These were all core questions that were considered by Arm experts and the academics in a two-day meetup at Arm's Cambridge headquarters.

The Journey to Securing Edge Devices

Imperial College London

Hamed Haddadi (Imperial College London)

With the rapid deployment of edge devices, it is critical to ensure we explore how to ensure privacy and trust in home gateways. This **work is part of an EPSRC Open Fellowship (Plus)**, supported by Arm, that investigates ways of bringing trust, privacy and attestation into models underpinning ambient experiences. It explores how we can enable personalization in experiences while pushing the boundaries of handling personal data.

The hope is to establish a framework that uses the latest architectural and security features in edge devices to help ensure privacy and a user-centric ecosystem. This will enable service providers to have trust in systems via attestation without users having to reveal sensitive personal information to the cloud-based centralized systems.

Evolving Sound Recognition to Monitor Health Conditions

Cecilia Mascolo (University of Cambridge)

As we explore ambient intelligence as a path for evolving medical ambient experiences, there is existing helpful research which uses sound recognition to monitor health, activity, gait, and heart rate. The UKRI-funded project, looking at respiratory infection progression detection, began its studies using mobile devices to **record coughs and speech to monitor COVID progression**. There is also work exploring heart-rate extraction from abdominal audio signals using a belt, so it's easy to see how our devices and possessions will evolve to help deploy ambient experiences at scale. Ongoing work is exploring how to improve ML models so that we can deploy continual learning on embedded devices and MCUs so that models can run on consumer devices to improve privacy.

Why Machine Body Language Will Need to Improve to Enable Ambient Experiences

Yvonne Rogers (UCL)

Ambient experiences will rely heavily on non-physical touch, and to achieve that machines will need to understand more about our physical and body language to process what we think and feel, are doing or are about to do. In contrast, current smart speakers miss out on this richness of body language, primarily relying on voice commands only. In a study called **Machine Body Language: Expressing a Smart Speaker's Activity with Intelligible Physical Motion** (Mirzel Avdic, Nicolai Marquardt, Yvonne Rogers and Jo Vermeulen), QUBI was developed as an alternative smart speaker that has expressive physical motion built into it to provide cues about its underlying behavior and activities.

These include stretching, nodding, turning, shrugging, wiggling, pointing, and leaning forwards and backwards. A qualitative study revealed how participants engaged with QUBI and found its expressive physical motions provided a much richer form of communication. Enabling the smart speaker to use a range of physical movements was found to enhance user interactions through augmenting voice instructions. In particular, it was able to provide additional information about the smart speaker's state and ongoing activities, and even use inferred cues to delight users.

The Key Use Cases

‘Human Digital Augmentation’ and Healthcare

The opportunities**:** Human digital augmentation essentially means the ability to amplify human cognition, including decision making and memory, thanks to a range of digitally connected devices around the individual.

A seminal example of human digital augmentation is the amplification of human senses – seeing, hearing or even touching and smelling – to unprecedented levels. Essentially becoming a “digital sixth sense.” Human digital augmentation is likely to be achieved via today’s smartphones, future augmented reality (AR) smart glasses or ‘hearables,’ or even other devices.

When combined with ambient compute systems, these devices could bring sounds to the fore that are important to the user and the environments they are in, like the sounds of a car when a person is crossing the road at a blind corner or from quiet electric vehicles. The amplification of human senses also has profound implications for those who are hard of hearing, with devices like hearing aids or even new hearables having the potential to provide advanced hearing capabilities.

For healthcare, ambient computing could lead to future smart hospitals and care homes that detect physical or physiological movements, such as breathing, heart rates, or even falls, among patients through simple sensors that are installed at various points in the building. This means that any healthcare issues are identified early without the need for constant supervision or without the need for each patient to have their own personal device.

Moreover, ambient clinical intelligence may use advanced, voice-enabled AI to automatically document conversations between physicians, patients, and families, rather than relying on paperwork from memory after these encounters. This helps save health services time and improve the accuracy of what was agreed with patients.

Meanwhile, healthcare use cases on wearable devices could advance through ambient computing, with health and fitness recommendations being extended into other devices and services. For example, this could mean presenting different meal options based on the health needs of individuals. Biometric data from these wearable devices could also be used to inform music and lighting choices in the home.

The challenges**:** There are three key challenges associated with human digital augmentation and healthcare ambient experiences. Firstly, the technologies, with devices like AR wearables and hearables still not commonplace on the mass market or affordable for the general population. Secondly, the cultural acceptance of these experiences and the future devices that will be needed. For example, research has shown that the perceived social stigma of using hearing aids delays consumers using them for over ten years after their hearing deteriorates. However, the mainstream success of technology to deliver truly life-changing experiences through the amplification of human senses could help to remove such stigmas and increase adoption of future devices. The third challenge is the need for greater collaboration, connectivity and interoperability across the many sensors and actuators that are installed in different environments to make these human digital augmentation and healthcare experiences a reality.

Acceleration of Ambient in Buildings, Public Spaces, and Public Transport

The opportunities: Various ambient computing experiences already take place in public spaces and on public transport. For example, there are sensors in trains that detect whether certain carriages are busy or not and which toilets are occupied, and then communicate that information to passengers. However, this could evolve to real-time directional instructions through indoor geolocation services to guide users to the right space for them based on their travelling preferences and context within the train carriage.

Meanwhile in buildings, ambient experiences will be more seamless, providing more relevant insights for the user and those around them. Future workplaces will have the capability of automatically booking desks or rooms for workers as they walk into the building. These ambient buildings could even deliver automated cleaning schedules based on dynamic real-time information showing parts of the building that are occupied or not in use.

How Invisible Monitoring Could Enable Ambient Experiences

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Alex Casson (University of Manchester)

To realize the vision of ambient experiences, we must gather more data from wearables and smart clothing to learn patterns from individuals. The **University of Manchester's research into monitoring of foot temperatures with personalized 3D-printed wearables** could provide an interesting starting point to exploring how we monitor footfall in homes, offices and cities. Similarly, its research shows that long-term management of diabetic foot ulcers with wearables can reduce incidence and recurrence of this condition – showing promising signs of how this work could enable some of the healthcare examples cited in this paper. The research is ongoing, and is currently exploring how biodegradable electronics could aid this study further, increasing recyclability and minimizing electronic waste from ambient experiences – watch this space.

The challenges: Five core challenges to this ambient computing use case were identified – connectivity, interoperability, accessibility, technology that is 'built to last,' and security and privacy.

Connectivity: The wireless connectivity required to enable ambient experiences in buildings, public spaces and public transport remains a challenge and still patchy among big crowds. The challenge is the compatibility between the many different network providers and devices, which slows down connectivity. To connect to different networks, devices have to go through different gateways and eventually the cloud for proper data exchange before going back to the device.

Interoperability: Collaborations across devices from different vendors and operating systems is essential for ambient computing experiences, but far too complex today – even for relatively simple devices that do not come from the same vendor. For devices to collaborate, they have to go to a cloud service that abstracts the local interoperability issues by centralizing signals. This slows down the overall experience and can also impact the safeguarding of security and privacy for the user (more on that later). This challenge is applicable across both IoT and consumer technology markets.

Accessibility: There are accessibility challenges associated with the technologies that will be required for future ambient computing experiences, as not everyone will be able to afford the latest smartphones or other enriched products that are set to be the gateways to enable these ambient experiences. The accessibility challenge extends beyond affordability, as not everyone will have the necessary level of technology skills to use these devices effectively, with some unable to use them at all.

Technology that is 'built to last': Focusing on buildings, embedded technology can be hard to replace once it is deployed, so whatever is installed must be 'built to last' through highly capable hardware. This also has positive implications for sustainability, as longer lasting technologies are more power efficient and need to be replaced less often which means less materials. Finally, the technology also needs to be 'software defined' with the ability to continuously add new, more advanced features via software updates through these highly capable hardware platforms.

Security and privacy: Due to the collection of personal data in these public spaces, protecting people's privacy is a big challenge for this use case. Many enhanced security technologies are already in place today, but there will need to be additional measures and protections to appropriately handle sensitive information.

This requires "privacy-preserving analytics" across technologies to ensure the avalanche of data is protected, with secure maintenance and updates to devices also essential. The additional layer to this security challenge is the likely deployment of different levels of privacy for different situations and environments in public and private spaces.

More Personalized Environments to Promote Greater Accessibility

***The opportunities*:** Ambient computing, especially its ability to provide more personalized environments, offers multiple opportunities to positively impact the lives of those with accessibility or neurodiversity challenges. For example, for those with neurodiversity, the impact from public environments could be altered through lessening the effects of noise and people in crowded spaces. This could be delivered through a concept such as "dynamic preference lists" that are personal to users. These lists adapt different environments based on user preferences, such as temperature and noise levels, or pointing people to more appropriate spaces.

Moreover, this also has positive implications for visually impaired people, as the personalized environments can provide them with information that is not normally available. For example, information about who is in a room during a meeting, who is speaking, and who has left, using spatial sensing and 3D audio.

***The challenges*:** These are largely the same as the previous use cases, especially in deploying technology that can be hard to replace and that has privacy and security challenges. There is also the challenge of not having experts or designers who specialize in creating technology in this space, with this limiting the scope of innovation.

The Ambient Computing Agreement

Based on the opportunities and challenges outlined above across the three key ambient computing use cases, Arm and the academic experts have built out an 'ambient agreement' of points that need to be explored further through collaborative research to make ambient experiences a reality.

- **Ensure ambient experiences provide "tech for good:"** This means getting the balance right between technology push and societal pull. Technology push is not just about marketing opportunities, but about making substantial real-world improvements to people's lives and to our planet through ambient experiences, particularly the key use cases outlined in this document.
- **Embed security and establish trust:** This will help companies adhere to the relevant regulations that will apply to ambient computing. To achieve security and trust, we must of course establish devices that are based on a hardware root of trust, but also address accountability, fairness, transparency, and ethics. We also need to ensure that the wider industry can detect and respond to attacks before they affect an entire network.
- **Protect the privacy of personal data:** Any data processing through ambient computing must take place in a "privacy-centric" way. This means protecting personal data from being accessed by systems or software that should not be able to access it. It also means giving the user choices in how their personal data is used through well-defined interfaces that allow them to express their privacy preferences.
- **Develop policies, best practices, and standards:** These will help the ongoing evolution of ambient computing, while promoting greater contextual awareness and better tailored, more relevant experiences for users.
- **Improve experiences without physical touch:** Human computer interaction (HCI) will change over time to enable ambient experiences to happen seamlessly without physical contact with devices. Features like voice commands and gesture control will become more important, alongside intent discovery, so that we can identify ahead of time what users may want to experience next.
- **Invest in interoperability and ensure connectivity while on the move:** High levels of interoperability will be a key part of ensuring that all the highly connected computing systems deliver seamless, personalized ambient experiences. As ambient experiences will need to manage consumers being "on the move", connectivity and location technologies will need to improve to enable the continuation of these experiences.
- **Focus on low power solutions:** Ambient computing will require more advanced workloads, but this needs to take place on low-power technologies, including sensors, 'at the edge' to ensure quicker, more secure ambient experiences. Due to the continuous nature of ambient computing, compute will need to be "always on" but in a way that is power efficient and sustainable. It will be important that systems adapt, and so on-device ML training becomes important compared to today's devices, where new learning may be performed on the cloud.
- **Ensure long-lasting, reliable, and software-compatible compute platforms:** To ensure hardware has a long lifecycle, we need hardware platforms that enable new features to be continuously added across the ambient computing world, with all these technologies compatible with the latest software development platforms. This will avoid installed technologies, especially those that are hard-to-reach in buildings, becoming quickly redundant and irrelevant.
- **Consider appropriate computing and distribution of intelligence:** As data will be fused from multiple data sources, we need to ensure that there is a method of fusing the data and managing competing computing demands. We also need to consider how the endpoints and edge interact with each other to enable the personalization of ambient experiences.

At the heart of this ambient agreement is the need for a reliable, secure hardware foundation capable of managing large amounts of data alongside fluid software deployment, so developers can keep adding more features and innovations. As the world's most pervasive compute platform with technologies across the entire spectrum, from low-power sensors to large-scale data centers, this is the role that Arm will play in the ambient computing future.

This ambient agreement that has been signed by the following participants:

Nicholas Cook, Senior Principal Systems Architect and Distinguished Engineer, Architecture and Technology Group, Arm

Paul Marshall, Associate Professor of HCI, University of Bristol

Cecilia Mascolo, Professor of Mobile Systems, University of Cambridge

Hamed Haddadi, Reader in Human Centred Systems, University of Cambridge

Björn Schuller, Professor of AI, Imperial College London

Nigel Davies, Professor of Computer Science, Lancaster University

Alex Casson, Professor of Biomedical Engineering, University of Manchester

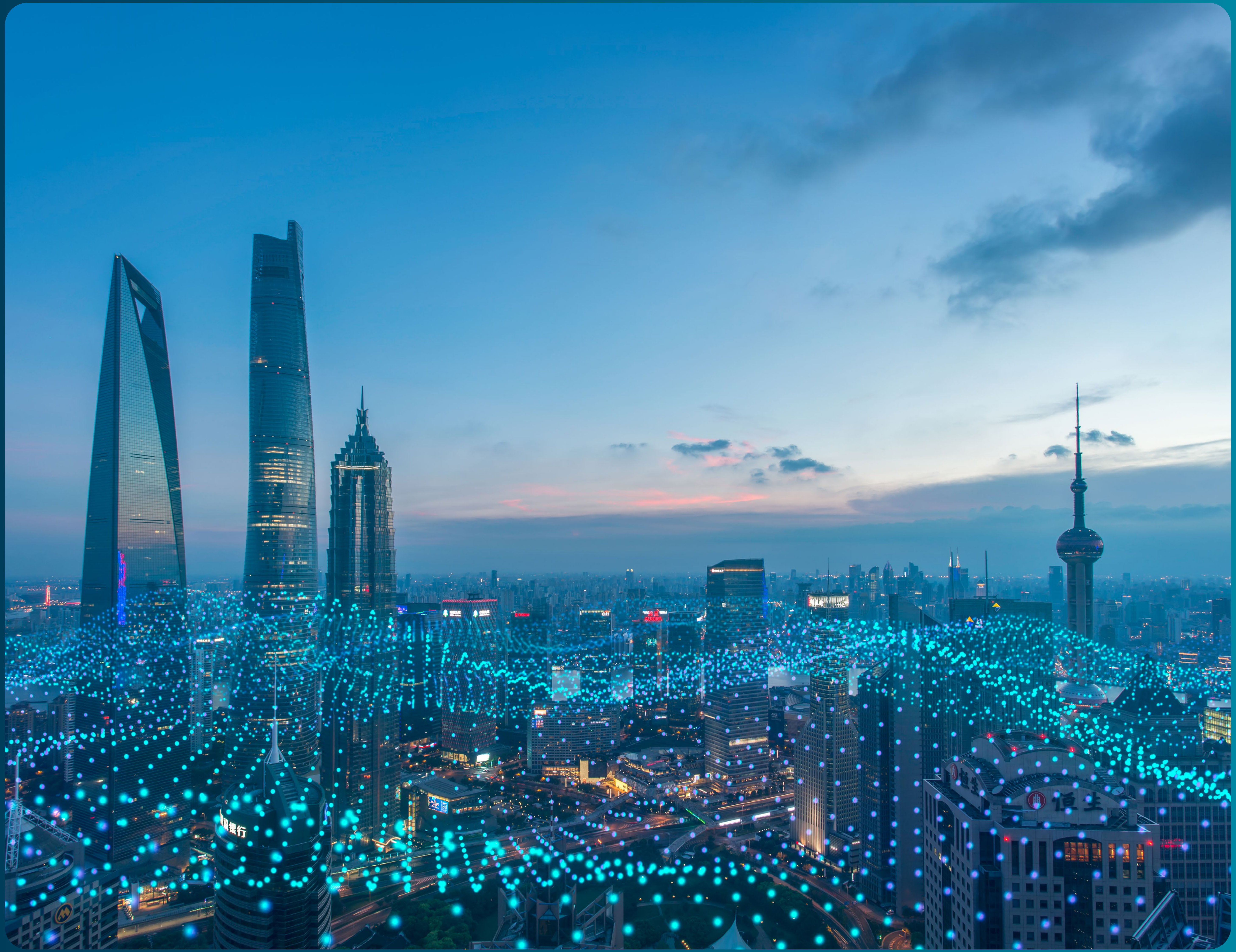
Caroline Jay, Professor of Computer Science, University of Manchester

Alex Rogers, Professor of Computer Science, University of Oxford

Richard Gomer, Lecturer in Computer Science and HCI, University of Southampton

Yvonne Rogers, Professor of Interaction Design, UCL

As part of the mandate of this ambient computing workshop group, we will continue to discuss these key ambient use cases, opportunities, and challenges, while working to ensure that this ambient agreement becomes a reality.



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