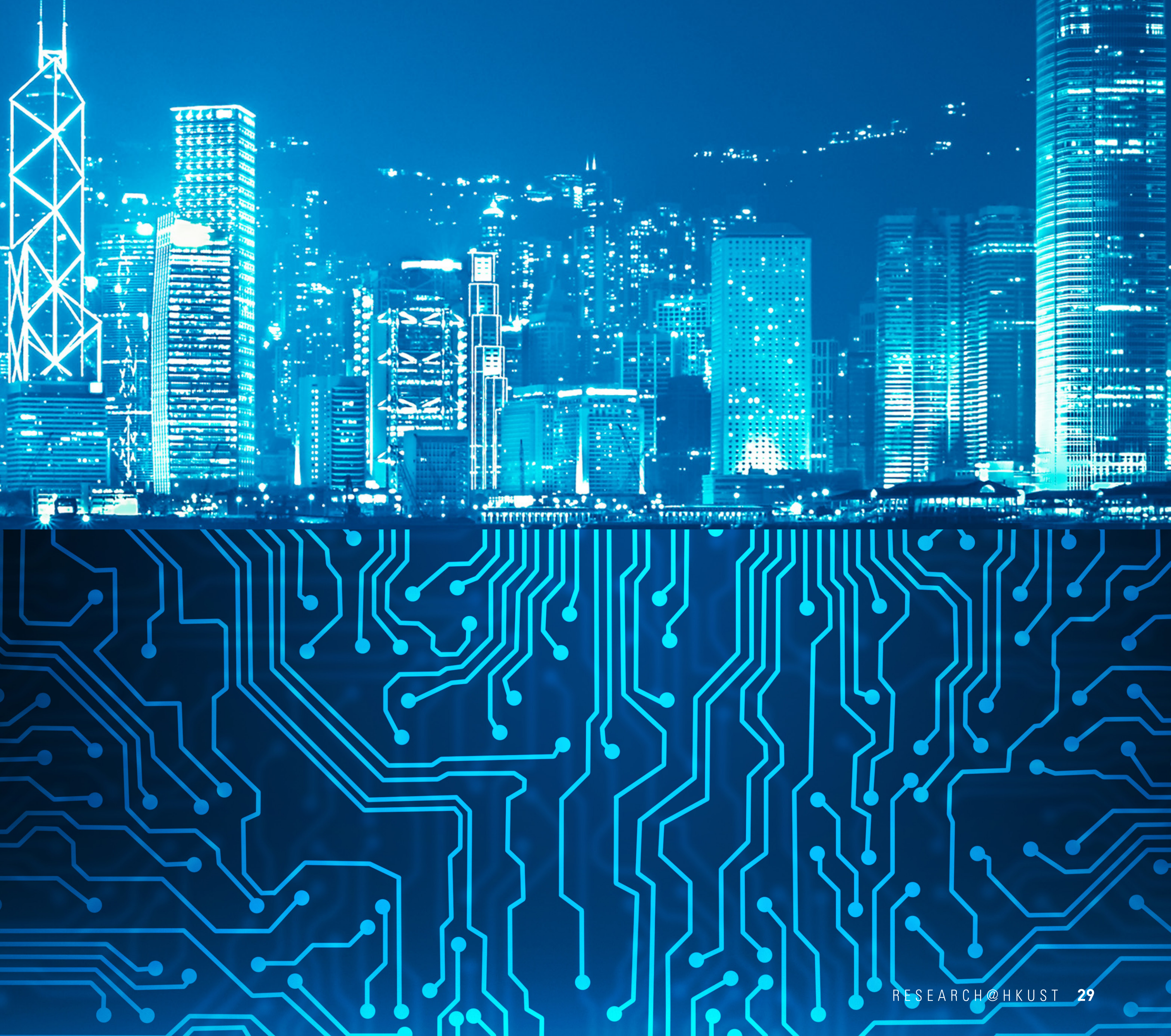
# SMART LIVING

Next-generation mobile networks, or 5G, are set to transform the future. But in what ways will this versatile world of faster and more reliable mobile communications actually reshape people's lives? Scientists and engineers at HKUST are at the forefront of such pivotal change, with a range of advanced technologies under development that seek to utilize the 5G wireless platform to empower individuals' patterns of life. Get ready to explore novel devices for personal health monitoring, your own air pollution avoidance strategies, as well as responsive energy-saving building controls and materials. Step into the smart life.



## Healthier Options

The era of connectivity being ushered in by 5G is often referred to as the “Internet-of-Things” (IoT), where billions of tiny sensing devices are embedded in everyday gadgets and devices, interconnected via a wireless infrastructure that enables ubiquitous sensing and communication. However, it is more the “Internet-of-Everything” that will characterize the digital landscape, from the perspective of computer science engineer Prof Qian Zhang and her researchers.

The HKUST team’s goal is to bring the benefits of such development down to the individual level, particularly to curb unhealthy lifestyle behaviors early and to boost the prevention of chronic diseases. Conditions such as diabetes, heart disease, cancer, and stroke are forecast by the World Health Organization to rise to 73% of all deaths by 2020 and comprise 60% of the global burden of disease.

Prof Zhang, a specialist in mobile and spectrum management of wireless networks and mobile communications, and her team are seeking a holistic approach to reduce those estimates. They aim to do so by looking at ways of understanding people’s current levels of health and making the relevant data accessible to encourage personal lifestyle adjustments. This involves the design of novel sensing applications, embedding artificial intelligence and data analytics built on superfast connectivity in devices that can monitor, log, recognize, and analyze patterns with little inconvenience to the user; and the provision of such information to healthcare providers, who recommend or deliver targeted strategies.


> “The Internet-of-Everything helps us to monitor, analyze, and adjust our daily behaviors for smarter and healthier living”

**PROF QIAN ZHANG**
Tencent Professor of Engineering,
Chair Professor of Computer Science and Engineering

As a result, the team has developed intriguing monitoring devices, including a special pillow to record changing sleep patterns, wearables such as glasses, and other smart contactless devices that can measure how and what we eat, to raise awareness and try to prevent health conditions from arising in the first place.

## Sleeping

The Zhang team has designed a smartphone-based auto-adjustable pillow system that detects, monitors, and treats the nighttime breathing difficulty known as sleep apnea. The system can assess whether the data collected by the wearable device actually represents a person experiencing sleep apnea or is simply a result of “signal noise”. Conventional diagnosis requires a user to attend a sleep center and does not include treatment.

Using a blood oxygen sensor and novel algorithms, the sleep apnea event can be detected wirelessly in real time, and the height and shape of the pillow automatically adjusted. Through continuous monitoring of blood oxygen levels, the data collected and analyzed by the system can evaluate the pillow adjustment and select a suitable position. In trials on 40 patients, the portable and cost-effective system reduced the duration and number of sleep apnea events by more than 50%. The HKUST team was among the first to propose and implement such a combined detection, monitoring, and treatment device for sleep apnea. The technology has now been patented and certified by the then-China Food and Drug Administration (now renamed as the National Medical Products Administration) after collaborations and clinical trials with Shenzhen People’s Hospital.

## Eating

Moving on from sleep, Prof Zhang and her team started to explore novel routes for diet monitoring – another vital aspect of personal health management and disease prevention. The conventional method to track diet is to manually keep a log, which requires discipline on the part of the subject. Wireless-enabled diet-monitoring spectacles, devised by Prof Zhang, meant this process could be automated by placing an electromyography sensor into the temple of the eyeglasses to measure movement of the temporalis muscle used for chewing. The prototype comprised a sensor, microcontroller SD shield/card, and Bluetooth radio. Working together with a smartphone, the spectacles achieved up to 96% accuracy for counting the number of chewing cycles and up to 90.8% accuracy for classifying five food types, including potato chips, crackers, and corn *(IEEE Internet of Things Journal,* 2017*)*.

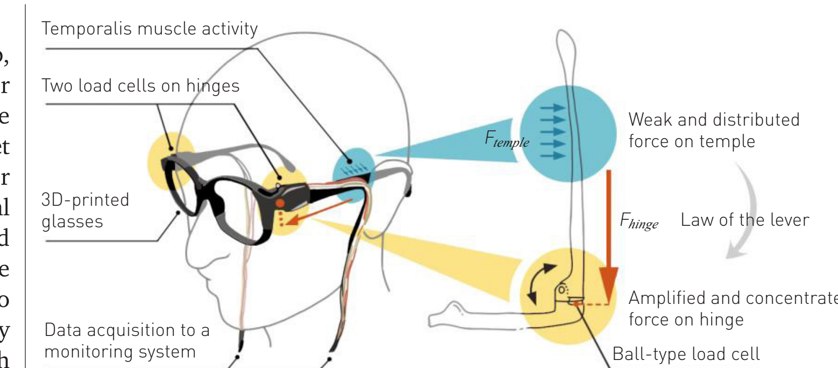



**Fig. 1** Sensors installed in smart glasses measure chewing cycles to determine intake schedule and amount, as well as the force of chewing to distinguish between five types of food with up to 96% and 90.8% accuracy, respectively

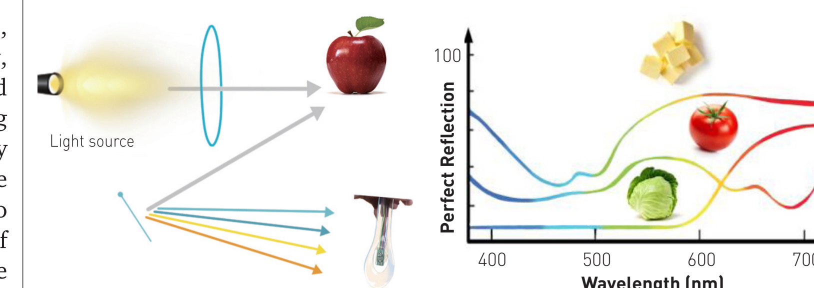



**Fig. 2** 3D-printed smart utensils with LEDs shine light onto food. A diffraction gradient separates the wavelengths of reflected light, while the chemical composition of the food dictates the percentage of the light reflected. The specialized machine-learning algorithm analyzes the combination of both values to detect 20 types of food and six types of drinks with 93% accuracy. Data is transmitted to a smartphone for further processing via Bluetooth.

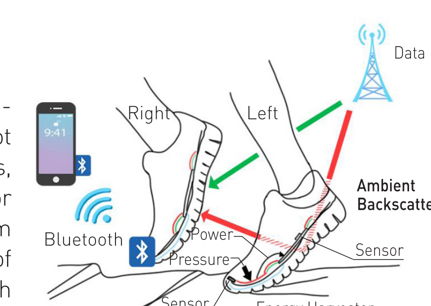
However, as wearables still require the individual to make a conscious effort, Prof Zhang sought to advance this “on-body” technology to an “off-body” solution. The result was Smart-U utensils, designed to unobtrusively recognize the contents of a meal while it is being eaten.

Employing spectroscopy as the underlying principle, the prototype utensil uses an array of sequentially-modulated LEDs as light sources to capture the spectra reflected by the foodstuff. By combining the wavelengths and intensities of the reflected light, both determined by the composition of the food, the prototype utensil could then analyze and recognize 20 types of food, including pork, beef, and carrot with 93% accuracy; while a prototype glass could recognize six types of drinks. Potential uses include tracking food intake and providing personalized food suggestions based on prior consumption and recommended nutrients *(IEEE INFOCOM,* 2018*)*.

Prof Zhang is the recipient of a 2017 Natural Sciences for Research Excellence Award (First Class) from the Chinese Institute of Electronics, 2012 Ho Leung Ho Lee Foundation Science and Technology Innovation Award, and 2012 China Young Scientist Award. She is also a Fellow of IEEE and holds more than 50 patents.

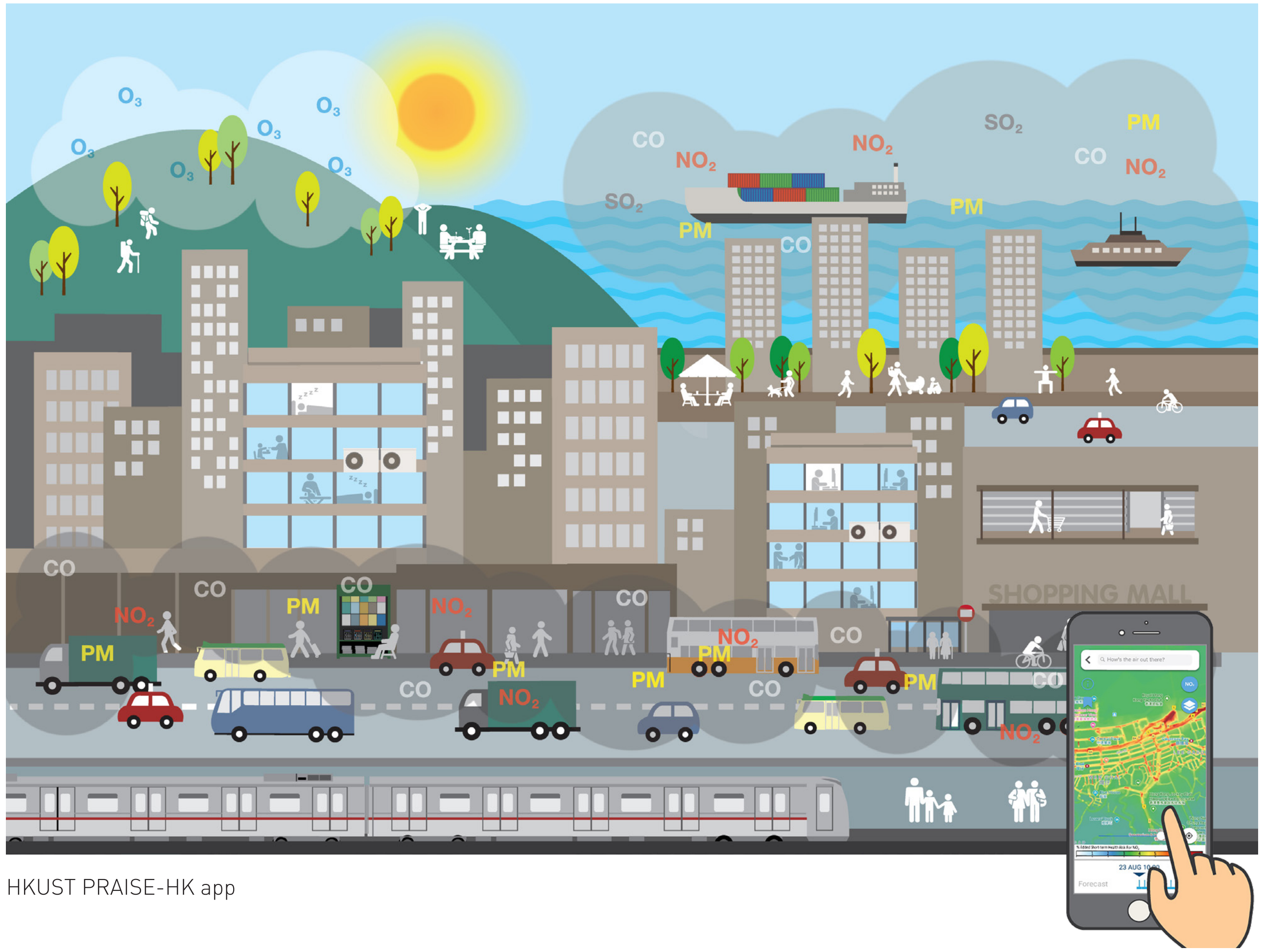
## POWERING CHANGE

The tiny size of sensors involved in ubiquitous and contactless sensing does not allow much room for bulky batteries, making energy consumption a major issue. Prof Qian Zhang and her team leveraged the reflective properties of Internet-of-Things devices along with radio frequency signals already in the environment – including television and Wi-Fi, known as ambient backscatter – to eliminate the need for a battery. In a prototype of a battery-less pair of shoes, the team designed energy harvesting insoles, power management circuits, and an ambient backscatter module, complete with Bluetooth, to support its many applications. The team was the first in the world to achieve such an energy-harvesting platform in shoes *(IEEE INFOCOM,* 2017*)*.




Sensors such as an accelerometer, pulse sensor, and energy harvester are installed in the left shoe to register activity. The heat and kinetic energy harvested during walking is then used to transmit the activity to the other shoe through ambient backscatter, which is finally wirelessly communicated to the user’s smartphone, without the need of a battery.

# BREATHING SPACE




HKUST PRAISE-HK app

In addition to novel ways to boost healthy sleeping and eating, HKUST researchers are empowering individuals to manage air pollution-related health conditions, such as allergies and asthma, and their overall well-being. This is being advanced through a first-of-its-kind mobile app combining world-leading air quality and transport modeling systems, exposure science, and big data analytics.

The initial phase of the three-stage project was completed in June 2019, with the app's public launch in Hong Kong. In its current phase, the technology is assisting users to manage and reduce their personal exposure to air pollutants while on the move around the city. It does so by providing real-time street-level air quality information that allows users to take bad-air avoidance strategies when planning their routes. In later stages, it is expected to track indoor environments as well.

## Moving Around

The five-year initiative, funded by HSBC's 150th Anniversary Charity Program, is known as the Personalized Real-time Air Quality Informatics System for Exposure – Hong Kong (PRAISE-HK). Its multidisciplinary HKUST research team is being led by air quality management expert Prof Alexis Lau. Among its breakthroughs, the project introduces the novel paradigm of managing personal exposure to pollution rather than the current air quality concentration management that focuses on controlling for average concentrations.

"Exposure here means how much air pollution a person experiences in a 24-hour period, not only when going to work, and walking around the streets, but also what he or she may be exposed to in their office and at home," Prof Lau said. "We aim to give people their air exposure patterns and then make suggestions as to how they may reduce such exposure."

## A Healthy Approach

Air quality at a particular location is affected by diverse factors, such as the source of air pollution, degree of traffic congestion, and wind direction. Prof Lau and his team have integrated all these factors through real-time data obtained from the Hong Kong government's Transport and Environmental Protection Departments in a unique data-fusion system. The team's novel algorithm is the intelligence behind the data modeling, and is capable of achieving unprecedented forecast accuracy of an index of agreement of more than 90%.

For a highly-urbanized area like Hong Kong, real-time availability of traffic conditions on major roads is another key element that contributes toward higher-accuracy analysis of emissions from transport, a part of the project guided by the expertise of dynamic transportation specialist Prof Hong Kam Lo. To make this feasible, Prof Lo built a dynamic public transport modeling system that leverages and enhances open-source traffic simulator software MATSim, Hong Kong's road network, and data on how and when people travel. The novel planning system can model travel plans down to the individual level in what the researchers refer to as "activity-based modeling", providing assessment of traffic speed, volume, and transport emissions, and ultimately a more accurate picture of the air quality data at the roadside level.

"We could not deal with these types of interactions previously," he said. "Now, using the very detailed information available and big data analytical methods, we can fuse these variables into our system, a refinement that is not being done anywhere else."

**PROF ALEXIS LAU**
Professor of Environment and Sustainability, Civil and Environmental Engineering

> "When people thought about air quality in the old days, they would feel that controlling air quality was out of their hands. Now we are showing that a lot of things can be done"

The PRAISE-HK project will not only empower individuals, but also move overall air quality management to the next stage of development, enabling decision-makers to identify hotspots, target more precisely the causes of pollution, and define methods to improve the situation. Currently, if concentrations are deemed too high, across-the-board requirements are usually put in place on sources of pollution to control their emissions. "To boost public health, we need to go beyond improving the average. We need to understand where and when people have their highest exposure to pollution and target those areas for improvement," Prof Lau noted. The research is being conducted in conjuction with the World Health Organization, United States Environmental Protection Agency, and other international scientists and agencies.

## PRAISE-HK INTERFACE

Air Quality Health Index (AQHI) | Risk composition | 48-hour air quality forecast | Spatial distribution of AQHI | Frequented locations | Health advice based on real-time air quality

**Phase I – Real-time High-resolution Air Quality Map**
(Launched June 2019)
Users can tap a map on the PRAISE-HK smartphone app to review outdoor air quality at any location in the city (sensitivity of up to 2m), along with the health risks associated with such air quality, to guide them to choose healthier routes or destinations. The app is also capable of displaying a 48-hour air quality forecast at said locations as well as providing health alerts.

**Phase II – Air Pollution Total Exposure Health-Risk Review**
(Targeted launch – June 2020)
This will include readings from selected indoor locations as well as outdoor environments to provide a total exposure review of a person's travel history and to plan future itineraries that avoid particular air pollution hotspots. Such capabilities bring air management down to the individual level. Highly-accurate portable sensing devices were designed to obtain indoor to outdoor air quality ratios, such as high-rise and underground levels, to establish baselines. In this phase, users can opt to input their personal health data that changes due to air quality.

**Phase III – Personal Air Quality & Health Alert Generator**
(Targeted launch - December 2021)
The final phase will include a personal air quality and health alert generator, built on data from the first two project phases. The function is capable of alerting and giving user recommendations, given that each person's lifestyle is likely to be different.

# STEPPING FORWARD

Our own two feet have often been left out of the planning strategies for urban transportation systems in the past. In a push for healthier urban living, this is set to change, especially in Hong Kong, where the government announced in the 2017 policy address that "walkability" would be given fresh emphasis as a way of moving around.

The city's existing approach to urban planning prioritizes vehicular traffic, while improvements to pedestrian traffic are often made through retrofitting pedestrian facilities. Now, data collection via location-aware sensors such as smartphones, has opened up urban informatics and big data analytics related to people's real activity patterns – how they travel, organize themselves, and use infrastructure.

To inform the smart policies that will help Hong Kong lead the way in developing strategies to promote walkability, Prof Hong Kam Lo draws upon his expertise in dynamic and stochastic traffic modeling. Prof Lo, along with fellow researchers, is in the process of building Hong Kong's first walking choice model through algorithms developed using multiple sources of data input. By building an intricate integrated building information modeling-3D geographic information system (BIM-3DGIS), the modeling system will enable network accessibility

"By making walkability an integral part of transport policy-making, Hong Kong can be an example to the world"

**PROF HONG KAM LO**
Chair Professor and Head, Department of Civil and Environmental Engineering

analysis and 3D visualization, along with walking utility functions based on econometric analysis. The three-year "Walkability" project was launched in 2018 under the Strategic Public Policy Research Funding Scheme of the Policy Innovation and Co-ordination Office of the Hong Kong government.

Walking choice models are highly complex as they need to incorporate numerous microenvironmental variables in the analysis, including issues such as whether walkways are sheltered, their width and slope, the existence of stairs, and the quality of the pavement, among others. Focusing specifically on the Hong Kong urban areas of Kwun Tong and Tsuen Wan, the project uses extensive survey data collection to analyze people's propensity for walking, what infrastructure they are looking for or trying to avoid, and the concerns of special needs groups, such as the elderly and physically challenged. For example, the research team's preliminary analysis has shown that, on average, people are willing to walk an extra 17 meters to avoid every vertical meter of stairs.

The team's walking choice model will provide insights into who would benefit from a particular initiative, and how. Such evidence-based information is critical in justifying infrastructure investment. They will also undertake policy analysis and provide options for the government to make the city more pedestrian-friendly.

### HKUST GREAT SMART CITIES INSTITUTE: BUILDING A SMARTER AND BRIGHTER FUTURE

Green, resilient, empowering, adaptable, and transformative – HKUST's GREAT Smart Cities Institute seeks to advance science and technology for smart city development in all these ways, and more. The Institute's diverse, cross-disciplinary research projects and applications include the PRAISE-HK mobile app, Walkability, Smart Urban Water Supply Systems (see *Research@HKUST*, 2017), and Mitigating Urban Debris Flow (see *Research@HKUST*, 2017), among other large-scale projects. The Institute also seeks to guide policy formulation and foster the next generation of professional urban planners.

# SMART ECO-FRIENDLY BUILDINGS

Hong Kong currently has the world's second greatest carbon footprint per capita, with functioning buildings making up more than 50% of total energy consumption and using 90% of the city's electricity.

Now, imagine a building that turns the temperature in a room up or down, depending on the number of people inside – without human intervention. A building with the capability to sense when a dangerous gas is being emitted and also alert managers or owners ahead of a hazardous build-up. An institution with low-power, high-performance air conditioning, where energy consumption can be monitored down to each room while still achieving thermal comfort. All using practical, low-cost technologies that are energy efficient and environmentally friendly.

These are the advances being realized in two wide-reaching projects under the HKUST-MIT Research Alliance Consortium, with funding from the Hong Kong Innovation and Technology Fund. Both aim to make it possible for such developments to be commercialized into widely-available products that will assist the reduction in energy usage and carbon emissions; and are using Hong Kong as a platform to showcase the beneficial implications of their advances to the world.

**Flow measurement sensor** that is compact and low-cost in design, without the usually bulky packaging for conventional flow measurement tools. Through integration with a micro-controller unit, sensor fusion, and the control program, a new thermal comfort-based HVAC system with artificial intelligence can achieve 20% energy saving in comparison with commercial HVAC systems.

**Intelligent Heating, Ventilation and Air-conditioning (HVAC) system** seeks to reduce carbon footprint in indoor environments.

**Air quality sensor** that can operate at room temperature to monitor any gas leakage and alerts. The capability to operate at room temperature helps reduce power consumption by 200 times, compared with conventional tin-oxide sensors. The sensor utilizes nanostructured materials and a CMOS chip to sense an array of channels with their own signal conditioning circuitry and analog-to-digital converter (ADC) to detect and distinguish between different gases. A patent has been filed.

**Environmental energy harvesting technology** maximizes energy extraction from two sources in the environment – solar and radio frequency (Wi-Fi) – to generate electricity to enable self-powered multi-sensing devices and their sensors. Antenna research also helps to maximize Wi-Fi energy harvesting by using a multiple orthogonal design that can collect ambient radio frequency from different alignments and then convert it.

**Image sensor** detects if a room is occupied or vacant, and triggers environmental adjustments, such as air conditioning and lighting. It can also alert building management when a human has entered a particular area. The HKUST complementary metal-oxide-semiconductor (CMOS) image sensor uses an analog-to-information converter (AIC) rather than the traditional ADC for comprehensive imaging and processing, and its power consumption is one of the lowest in the world.

**Smart water quality sensor** recruits genetically engineered *E. coli* to autonomously detect water contaminants, such as cadmium and zinc, by harnessing biological sensor systems for contaminants. For pollutants beyond natural sensing systems, synthetic *E. coli* are engineered to serve as fluorescent light indicators to show the concentration of particles in a sample. Also included are an optical sensor that responds to and measures the intensity of fluorescent light emitted by the *E. coli*, as well as circuits for data collection and transmission.

## Smart Self-powered Multi-sensing Technologies

In the first project, coordinated by electronic and computer engineer Prof Chi Ying Tsui, a next-generation series of low-power and cost-effective sensors for measuring and analyzing images, air quality, water quality, temperature, humidity, and thermal insulation, is underway.

The sensors are integrated into a single multi-sensing device equipped with novel energy harvesting and power management technologies, allowing the device to power itself autonomously. Meanwhile, low-power radio frequency (Wi-Fi) communications as well as integrated circuit and system-level innovation provide the capability to

> We have set ourselves really stringent specifications of low power, low cost, self-calibration, and integration to be the driving force of innovation

**PROF CHI YING TSUI**
Professor of Electronic and Computer Engineering,
Head, Division of Integrative Systems and Design

transmit critical information to a base station or trigger an alarm. There is no need to connect the sensor devices to the mains, thus reducing the costs of installation, widening the options as to where they can be deployed, and lowering overall maintenance costs.

The energy harvesting technology is based on Prof Tsui's expertise in multiple-input, multiple-output (MIMOs) power management technology research, ongoing since the early 2000s. Prof Tsui's team employs a combination of solar and radio frequency energy sources to generate output for use in the sensor, the charging up of the small battery inside the integrated device, as well as wireless communication.

The key innovation lies in the new MIMO power management architecture that maximizes energy extraction and conversion. Intelligent circuits have been designed to ensure the solar cell is operating in conditions that will maximize its power and reduce its loss during conversion from solar to electrical power.

In the longer term, the project's novel technologies could also be employed in applications as diverse as toys and odor detectors in fridges.

## MEMS and Carbon Footprint

In the second research project, coordinated by mechanical engineering specialist Prof Yi-Kuen Lee, an intelligent heating, ventilation and air-conditioning (HVAC) system is being developed to reduce the carbon footprint in indoor environments. In Hong Kong, air conditioning in high-rise buildings accounts for around 30% of total energy consumption.

Prof Lee focuses on developing novel micro-electromechanical (MEMS) flow sensors. MEMS are tiny devices with moving parts, such as sensors, gears, and valves that are embedded in semiconductor chips. The aim is to develop a low-cost micro-energy sensor that can be deployed in each room, or different zones of buildings, providing a more detailed breakdown of energy consumption (for example, hourly, daily, monthly) than previously feasible, to help buildings achieve greater energy efficiency.

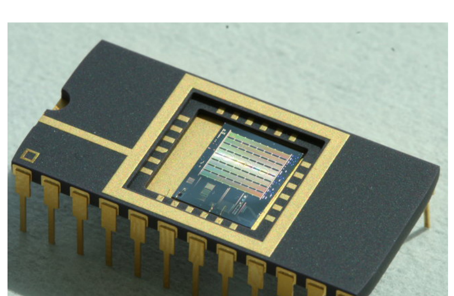
The HKUST researcher's innovative "system-on-chip" design comprises a compact, low-noise and low-power com-

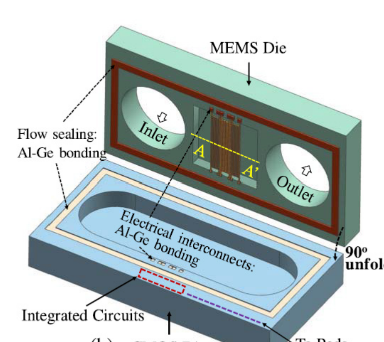
> While some people say fundamental research is impractical, it actually provides a great foundation to work on technology

**PROF YI-KUEN LEE**
Associate Professor of Chemical and Biological Engineering, Mechanical and Aerospace Engineering

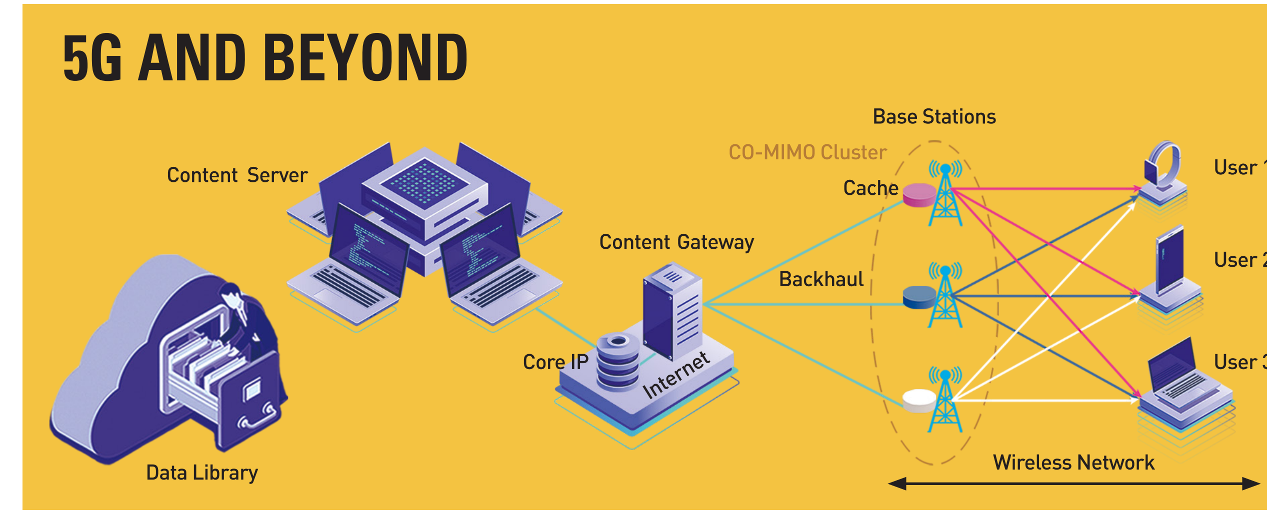
plementary metal-oxide-semiconductor (CMOS) thermal flow sensor to measure two-dimensional air velocity, when traditional flow measurement tools only make measurements in one dimension.

Prof Lee has optimized the system-level design through developing a general compact 1D model and collaborating with a commercial foundry to align the design with mature CMOS fabrication technology. The integrated design can significantly improve flow measurement accuracy to 1.6 millimeters per second, better than 3.8 millimeters per second according to the air speed standard of the United States using expensive optical instruments. It is able to provide a much quicker way to analyze sensitivity and power consumption to optimize devices and microsystem integration than employing time-consuming computational fluid dynamics models. Indeed, Prof Lee's theoretical flow sensor model could do the job a million times faster.






**LEFT**: Fabricated flow sensor chip; **RIGHT**: Wafer-level encapsulated flow sensor with readout integrated circuit and packaging design




Prof Lau discovered that a cache can be used at the edge of a wireless network, or base station, to store data such as a popular YouTube video that many users are trying to watch simultaneously. His novel physical layer caching technology transforms the underlying topology to significantly boost the transmission bit rates and capacities.

The recent arrival of fifth-generation (5G) mobile networks promises faster and more reliable mobile connections, with forecasts of 1,000 times greater demand capacity, and 500 billion devices connected to the Internet by 2030. The era of mobile connectivity being ushered in by 5G is expected to drive significant progress in entertainment, logistics, mobility, health, and other technologies, with some examples discussed earlier in this chapter.

A significant avenue to facilitate such development is a new "application-aware" framework where the individual needs and characteristics of different applications can be identified and utilized by the network for greater efficiency. Prof Vincent Lau, an expert in wireless information technology, is at the forefront of such advances.

## Speeding Up with Physical Layer Caching

One example of "application awareness" that Prof Lau has pioneered is "physical layer caching", which helps the wireless network deliver contents rather than random information.

Caching is beneficial as it stores data and reduces the number of hops that a packet of data has to make between the server and the user's computer. Prof Lau's research team is the first to make the groundbreaking discovery of using a cache at the edge of a wireless network, or base station.

Through cooperatively sharing data between base stations, Prof Lau's

> Future wireless networks will be integrated with applications in our everyday life

**PROF VINCENT LAU**
Chair Professor of Electronic and Computer Engineering

innovative Physical Layer Caching Model transforms the underlying architecture of the wireless network, from a less favorable interference channel topology to a more favorable broadcast channel topology, resulting in a significant boost to the transmission capacity. In doing so, the presence of caches at base stations improves speed and lowers the power requirement. Alternatively, using the same amount of power, the network can achieve a much higher bit rate or support more users.

Prof Lau became the first to publish on physical caching in 2013. His work has led to the discovery of storage as a new resource metric, in addition to the well-known power and bandwidth, to support content-centric communications.

A more challenging issue for Prof Lau is developing a caching algorithm to help the network decide what it should be caching, given that a base station always has limits on its storage capacity. This may help the industry set new standards for 6G wireless systems because caches have never been used at base stations before.

## Mission Critical Control – Safer, More Reliable

A second example of "application awareness" is integrated design for specific applications to achieve better performance in mission critical control, for example, autonomous vehicles' capability to avoid collisions. In this application, the goal of the wireless network is not only to maximize information capacity but also to achieve stabilization in a potentially unstable dynamic system through feedback control.

Prof Lau has combined his long-held interest in both communication and control theories to design a novel ultra-low latency multi-access protocol, by harnessing the signals transmitted by different sensors over the same radio resource block as well as developing an allocation algorithm that provides a flexible priority function to avoid congestion collapse when there are too many information requests from Internet-of-Things (IoT) sensors.

Such tactile latency can only be achieved with ultra-low latency communications enabled by 5G and beyond systems.