Engineering

Phone signals can help you find your way without GPS

Hui Chen & Henk Wymeersch

Existing telecommunications infrastructure could operate as a miniaturized global positioning system, offering submetre resolution in urban areas and indoors, where location information from satellites is often inaccurate. **See p.473**

It's hard to imagine ever consulting a paper map again. The information provided by global navigation satellite systems, such as the United States' GPS or China's BeiDou, has changed how we find our way in the world. But the little blue dot that represents this information on our smartphone screens often shows up far away from our actual location, especially in urban areas, tunnels or indoors. This is largely because satellite signals are weak and easily blocked by obstacles, or are sometimes even jammed intentionally. On page 473, Koelemeij *et al.*[1] show that telecommunications networks can overcome this problem by providing a terrestrial positioning system that does not rely on satellites.

Whereas animals are adept at navigating by myriad means, such as smell (salmon), magnetic fields (pigeons) and the topography of the ocean floor (dolphins), humans do so mainly by observing landmarks and using tools. From the earliest attempts to navigate by noting the positions of the Sun and stars, people have developed increasingly advanced techniques for determining location — eventually building celestial navigation equipment and the compass. However, celestial navigation requires a clear view of a particular constellation, and compasses provide only relative information about a person's position. The invention of a tool that could determine someone's absolute position using information from satellites was therefore a major development in the history of human navigation.

Current global navigation satellite systems consist of several satellites orbiting Earth that are tightly synchronized in time. These satellites work as anchors in the sense that their positions are always known, even though they move over time. Signals that are sent periodically by these satellites are processed by the receiver using special equipment — for example, a GPS sensor in a smartphone. This equipment calculates the distance that signals travelled from each satellite, by measuring their arrival times. A process known as trilateration then uses this information to pinpoint the receiver's location on Earth in terms of latitude, longitude and elevation[2]. Signals from at least four satellites must be received to complete this task, which can be challenging in urban areas.

The ubiquity of mobile-phone networks has prompted researchers and engineers to use the base stations in these networks for positioning[3]. A typical approach complements information from satellite signals with that of mobile-phone signals[4]. Unfortunately, mobile-phone networks alone cannot provide accurate positioning services, because their base stations are not tightly synchronized (a time delay of one nanosecond results in a location error of 30 centimetres, because the signal travels at the speed of light). The frequency bandwidth in current telecommunications networks is also insufficient to estimate the arrival time of signals accurately enough to provide precise location information. Alternative techniques exist[5], but these approaches have other drawbacks, such as high deployment costs and time-consuming computations, which limit their scalability.

Koelemeij *et al.* sought to overcome these limitations, specifically for positioning in urban areas, by proposing a hybrid optical–wireless system (Fig. 1). Their system uses a telecommunications technique known as orthogonal frequency-division multiplexing (OFDM) in transmitting multiplexed signals at a 'carrier' frequency of 3.96 gigahertz (1 GHz is 10^9 Hz), and with a bandwidth of 160 MHz, through several base stations. This large bandwidth means that the system can identify paths in which the signal is reflected by objects between each base station and the receiver. Making sure that the base stations are synchronized in time is the most challenging part of the problem, and this is solved by linking them with optical cables and implementing tailor-made timing protocols.

The position of the receiver is determined by first computing the time delay between the arrival of different signals, from which a location can be extracted with decimetre-level accuracy. Koelemeij *et al.* showed that this could be improved to a centimetre scale by taking advantage of information about the phase of the carrier wave (the fraction of

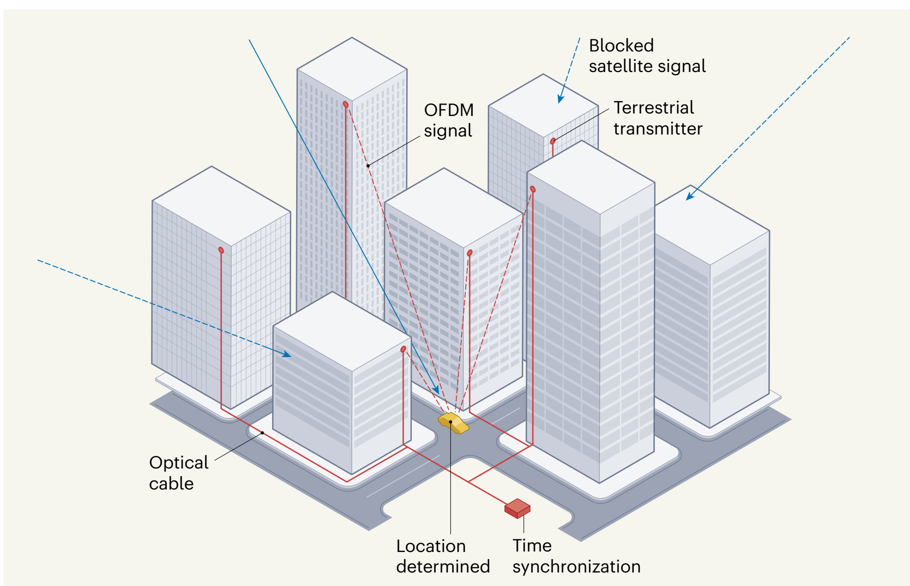

Figure 1 | A hybrid optical–wireless positioning system. Global navigation satellite systems offer useful location information, but their signals can be blocked in urban areas, leading to imprecise positioning. Koelemeij *et al.*[1] designed an alternative system that uses a telecommunications technique known as orthogonal frequency-division multiplexing (OFDM) to transmit multiplexed signals through terrestrial transmitters that are connected by optical cables and centrally synchronized. The transmitters are more likely to have a direct line of sight to the receiver than are satellites, and their optical links ensure that they are synchronized. The authors achieved centimetre-level positioning accuracy with their system, using existing telecommunications infrastructure.

the wave cycle that the signal has completed at any given time). By comparing this phase with that of an oscillator in the receiver, the system can estimate distances with an uncertainty that is smaller than the signal's wavelength, which is around 7.6 cm for the 3.96-GHz wave. One key advantage of the authors' system is that it is compatible with existing 4G and 5G telecommunications networks, which use the same type of multiplexed signal.

The decimetre-scale positioning accuracy reported by Koelemeij and colleagues is certainly impressive, especially because they achieved it using the existing telecommunications infrastructure. Nevertheless, the positioning scheme could be further improved, by adopting certain emerging communications technologies. Combining multiple antennas with millimetre-wavelength signals enables estimation of the angles of signal arrival and departure, as well as the difference in the time it takes the signal to travel between the user and several base stations[6]. With this information, a high level of accuracy can be maintained with fewer base stations and a reduced reliance on synchronization, by making use of natural reflections in the receiver's environment[7]. Knowing these angles makes it possible to estimate the orientation of the receiver as well as its location — a desirable feature of navigation systems[8].

In this respect, Koelemeij and colleagues' system would benefit from using higher-frequency signals than those implemented in their study. High-frequency signals have short wavelengths, which means that more antennas can be packed into the same area than can those that process low-frequency signals. For example, a 140-GHz signal can accommodate 25 times more antennas in the same area than can a 28-GHz wave. Having so many antennas enables measurement of the curvature of the signal's spherical wavefront, which can also provide valuable positional information[9].

One of the next steps for telecommunications networks will be the introduction of materials known as reconfigurable intelligent surfaces, which can be used to coat walls and objects in a receiver's environment. Such materials can be programmed to change the direction in which an incoming signal is reflected, providing a low-cost way of controlling signal propagation with very low power requirements[10].

These developments will all lead to improved location information that is expected to have exciting applications in a future network known as the Tactile Internet, which will provide information through touch, as well as visual and auditory signals. Accurate positional information could lead to 'smart cities', in which homes automatically turn on heating as their occupants get closer, and drones that deliver packages to recipients on the move. Koelemeij and colleagues' scheme brings these cities a step closer to reality.

Hui Chen and **Henk Wymeersch** are in the Department of Electrical Engineering, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden.
e-mails: hui.chen@chalmers.se; henkw@chalmers.se

1. Koelemeij, J. C. J. *et al. Nature* **611**, 473–478 (2022).
2. Hofmann-Wellenhof, B., Lichtenegger, H. & Wasle, E. *GNSS–Global Navigation Satellite Systems: GPS, GLONASS, Galileo, And More* (Springer, 2007).
3. del Peral-Rosado, J. A., Raulefs, R., López-Salcedo, J. A. & Seco-Granados, G. *IEEE Commun. Surv. Tut.* **20**, 1124–1148 (2017).
4. Kassas, Z. Z. M., Khalife, J., Shamaei, K. & Morales, J. *IEEE Signal Proc. Mag.* **34**, 111–124 (2017).
5. Zafari, F., Gkelias, A. & Leung, K. K. *IEEE Commun. Surv. Tut.* **21**, 2568–2599 (2019).
6. Koivisto, M. *et al. IEEE Trans. Wireless Commun.* **16**, 2866–2881 (2017).
7. Witrisal, K. *et al. IEEE Signal Process. Mag.* **33**, 59–70 (2016).
8. Mendrzik, R., Wymeersch, H., Bauch, G. & Abu-Shaban, Z. *IEEE Trans. Wireless Commun.* **18**, 93–107 (2018).
9. Guerra, A., Guidi, F., Dardari, D. & Djurić, P. M. *IEEE Trans. Signal Proc.* **69**, 5723–5738 (2021).
10. Elzanaty, A., Guerra, A., Guidi, F. & Alouini, M.-S. *IEEE Trans. Signal Proc.* **69**, 5386–5402 (2021).

The authors declare no competing interests.

Ecology

Neighbours and climate affect species extinction

Ellen I. Damschen

Predicting the risk of extinction from climate change requires an understanding of the interactions between species. An analysis of how changes in rainfall affect competition between plant species offers a way of tackling this challenge. **See p.507**

Anticipating how natural ecosystems will respond to climate change, and determining which species are most at risk of extinction, are crucial aspects of conservation work. On page 507, Van Dyke *et al.*[1] shed light on this timely issue.

Between about 10% and 50% of all species on Earth, including flowering plants, are predicted to be at high risk of extinction as a result of climate change[2]. Such predictions are almost always generated by considering how individual species respond to a changing climate, without taking into account their potential interactions with other species. This gap in our understanding is not due to a lack of recognition of the importance of species interactions, but reflects the enormous challenge of measuring the strength of species interactions in realistic field conditions, let alone considering how a changing climate might alter those interactions. Yet such estimates are clearly needed to provide realistic scenarios for the future that can guide conservation actions.

Van Dyke and colleagues provide a major advance in the prediction of species persistence under climate change by coupling a well-designed field experiment with predictive mathematical models in order to determine how climate change affects the outcome of competitive interactions. They obtained seeds of six plant species with a one-year life cycle from a biologically diverse ecosystem in which water is limited and drought is already causing species loss[3]. Sowing these seeds, the authors created experimental communities consisting of varying numbers of individuals of the same species or pairwise combinations of different species. Each of these one- or two-species communities, which developed from seeds sown to generate different population sizes, were subjected to either the ecosystem's current average precipitation or to a 20% reduction in the average precipitation — a scenario mimicking the decreases in rainfall predicted for the area as a result of future climate change. The effects on individual plant survival in each of these contexts were measured, and the data used in mathematical models to generate predictions for whether one or both species would persist. The authors conclude that modest changes in climate strikingly alter the outcome of competitive interactions between species, whereas those same rainfall changes have little effect on how species fare when grown alone. In most cases, the effect of competition on species persistence and coexistence was entirely different under the climate-change scenario compared with the patterns of persistence and coexistence observed under current conditions (Fig. 1).

Surprisingly, climate change was less likely to affect competition between species pairs that were more similar in terms of their roles or functions in the ecosystem. Foundational theories of ecosystem resilience predict that communities that contain species with very different functions will be more resilient in a