Jie YANG, Jing XU, Xiao LI, Shi JIN, Bo GAO, 2021. Integrated communication and localization in millimeter-wave systems. *Frontiers of Information Technology & Electronic Engineering*, 22(4):457-470.
https://doi.org/10.1631/FITEE.2000505

Integrated communication and localization in millimeter-wave systems

Key words: Millimeter-wave; Integrated communication and localization; Location-assisted communication; Extremely large antenna array; Reconfigurable intelligent surface; Artificial intelligence; Neural networks

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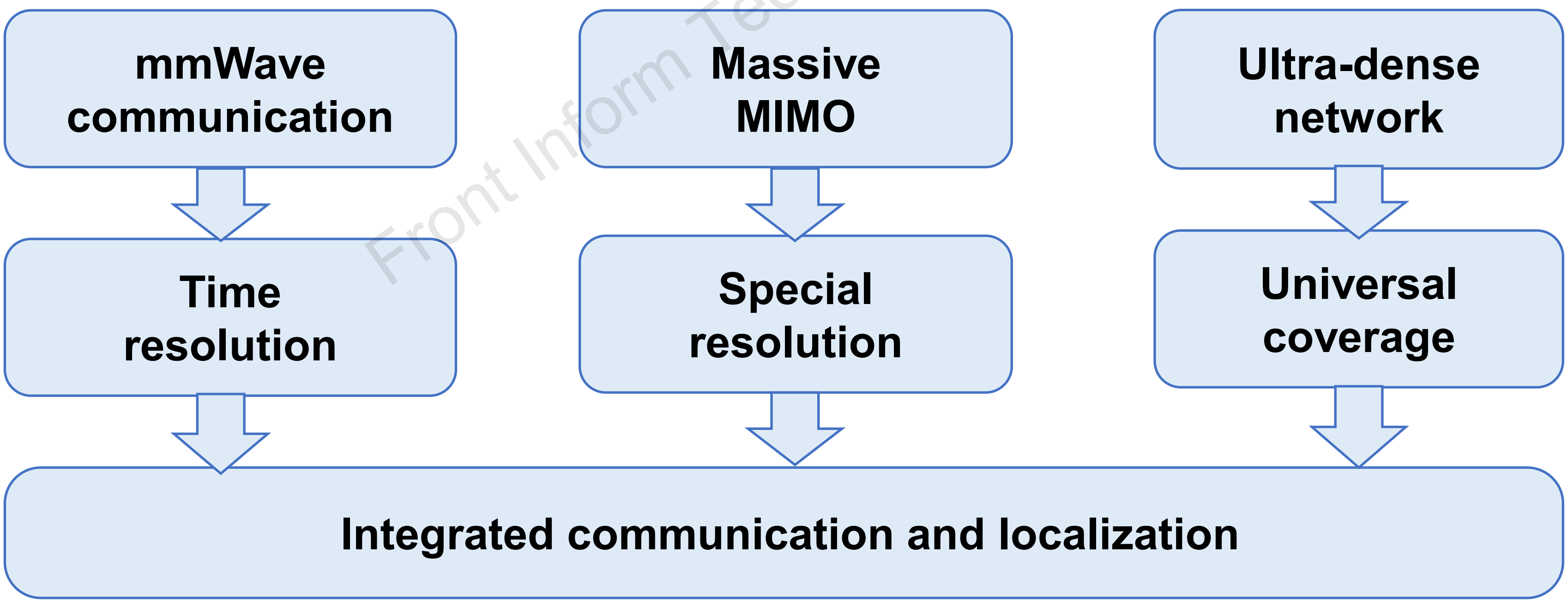
1 Motivation

- Millimeter-wave (mmWave) band communications are expected to play a pivotal role in the fifth-generation (5G) and upcoming sixth-generation (6G) mobile communication systems.
- The highly directional transmission makes localization a greatly desirable feature of mmWave communication systems.
- Although considerable advantages in integrating communication and localization in mmWave systems have been predicted, studies in this field have just started.



2 Integrated communication and localization

- A high degree of integration of advanced technologies in communication and localization at the level of hardware architecture and algorithm system
- Share the infrastructure and time-frequency-space resources of wireless communications

✓ Coordinating communication and localization can be empowered by the information interaction capability of the high-rate and low-delay mmWave communication systems

✓ The location can be used more flexibly to assist the beam training and prediction processes

2.1 Signal model and channel model

- **Signal model:** $y(t) = H(t) * x(t) + n(t)$
- **Channel model:** $H(t) = \sum_{l=0}^{L} \alpha_l a_{\mathrm{R}}(\theta_l^{\mathrm{az}}, \theta_l^{\mathrm{el}}) a_{\mathrm{T}}^{\mathrm{T}}(\phi_l^{\mathrm{az}}, \phi_l^{\mathrm{el}}) \delta(t - \tau_l) \mathrm{e}^{\mathrm{j}2\pi\nu_l t}$

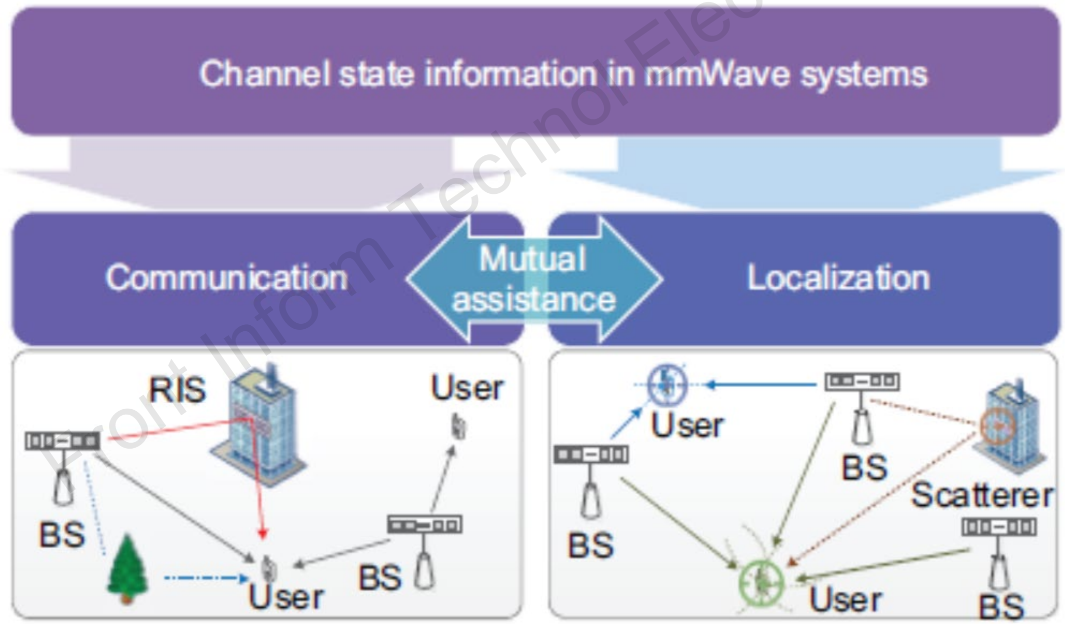
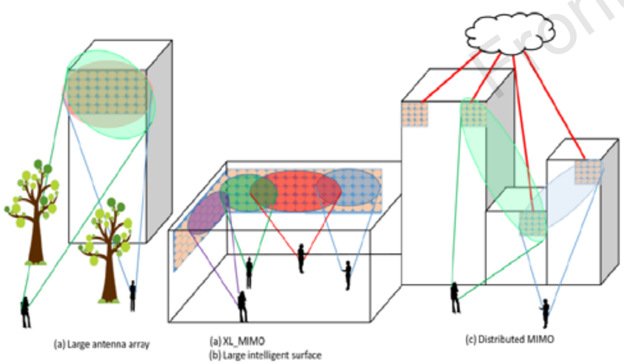


Fig. 1 Integrated communication and localization in millimeter-wave (mmWave) systems

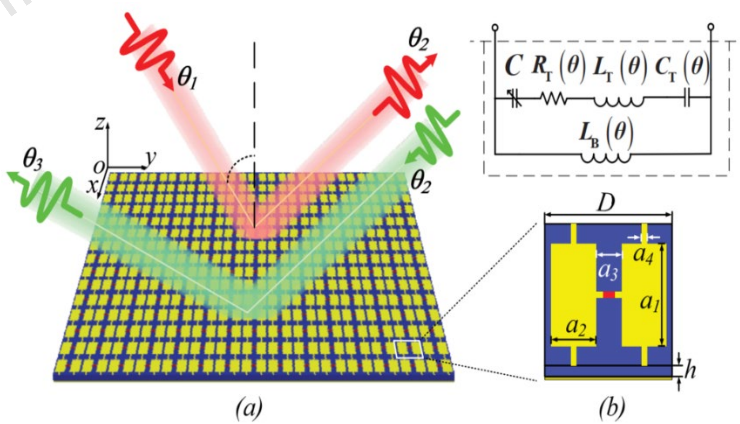
BS: base station; RIS: reconfigurable intelligent surface

2.2 Enabling technologies

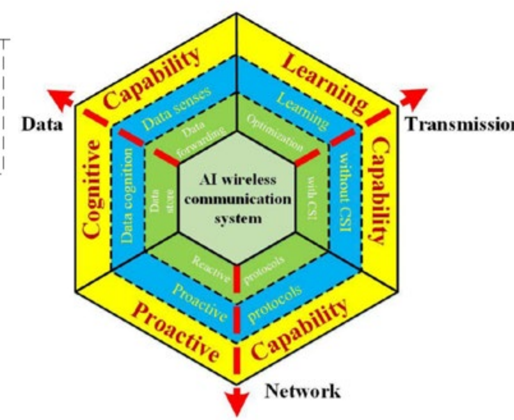
- ELAA techniques drive the antenna deployment towards larger apertures and greater numbers than those of commercial cellular systems. The inherent phase shifts in the space caused by spherical waves provide new opportunities for localization in ELAA systems.
- RIS is promising in extending the wireless communication range, facilitating NLoS communications, and providing low-cost cooperative localization opportunities.
- AI-based learning methods based on hybrid data and models have also emerged to reduce the training data and enhance the robustness of the algorithm.



ELAA



RIS



AI

3 Localization in mmWave systems

□ Goal

Estimate the location, velocity, and orientation of the *user-equipment* or *agent nodes* together with possible scatterers on the basis of a set of wireless reference signals transmitted or received by the *base stations* or *anchor nodes*.

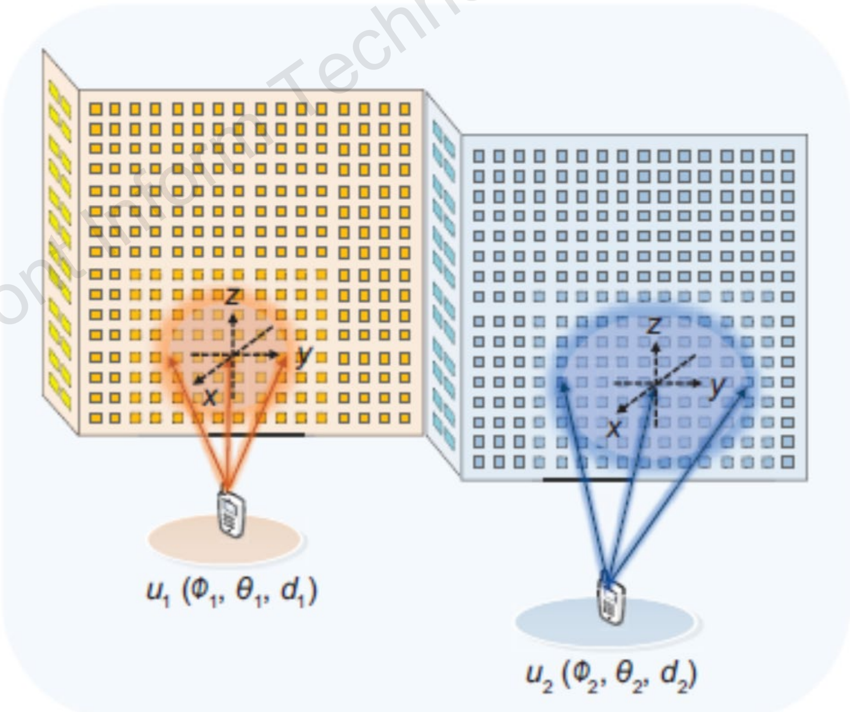
□ Advantages

- ✓ Deployment is convenient and cost-effective by reusing the infrastructure that is used for mmWave.
- ✓ Recycle real-time CSI that is already processed at the receiver in communication systems.
- ✓ Not intrusive (vs. sensor)
- ✓ Insensitive to lighting conditions (vs. video)
- ✓ Unprecedented time-frequency-spatial resolution (vs. WiFi)
- ✓ The high throughput offered by mmWave communication links can be leveraged to quickly and reliably share map and location information among different devices.

3.1 Localization with extremely large antenna array

- Allow the characterization of a path with a new parameter, i.e., the distance between the source and the reference point.

✓ Near-field effects facilitate the exploitation of the wave front curvature to jointly estimate the range and direction of the source.
✓ Remove synchronization
✓ Improve the accuracy of location



3.2 Localization with model-based neural networks

- To overcome the disadvantages of localization methods based on pure data or model, we propose a localization method based on hybrid data and model, i.e., the localization with model-based neural networks.
  - Retain the advantages of the model-based approach (determinacy and theoretical soundness) and powerful learning ability of the data-based approach.
  - Overcome the difficulties in accurate modeling and avoid the large requirement for time and computing resources.

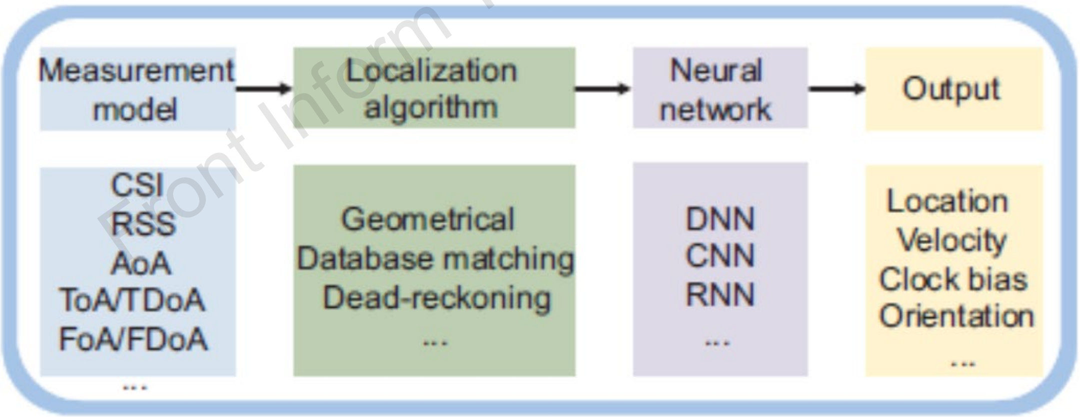
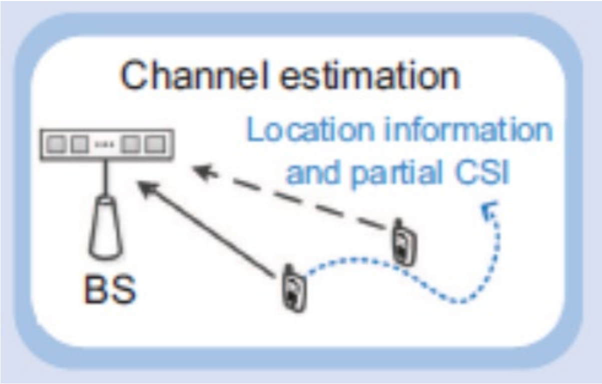


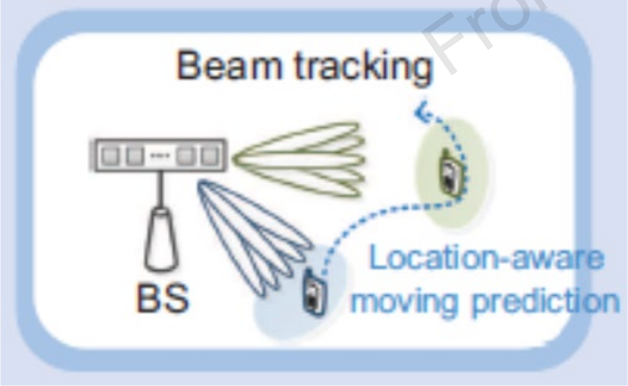
Fig. 3 Localization with model-based neural networks

4 Location-assisted mmWave communications

- Turn the traditional CSI-based communication solutions into hybrid CSI- and location-based solutions.

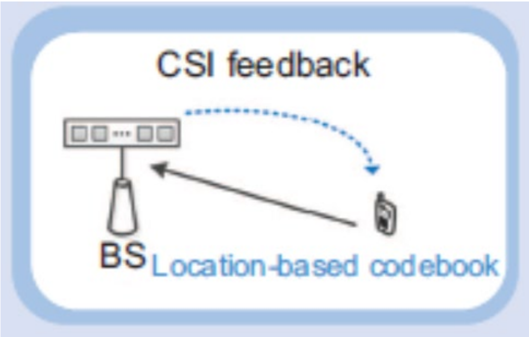


Coarse CSI can be predicted from the side information from the location and environment, and this prediction can be complemented with instantaneous small-scale information, thereby reducing communication overheads.

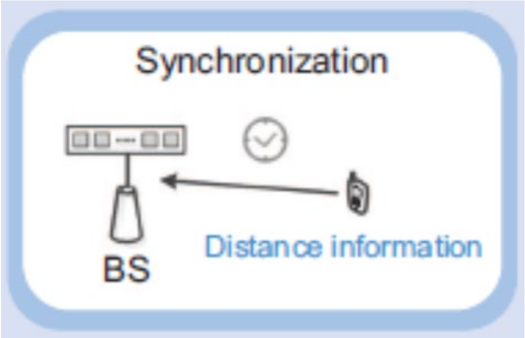


By using spatial movement coherence in combination with location prediction, the predicted coarse beam directions can be obtained to greatly narrow down the beam search area. In particular, the location information can significantly speed up the beam tracking process with a low overhead.

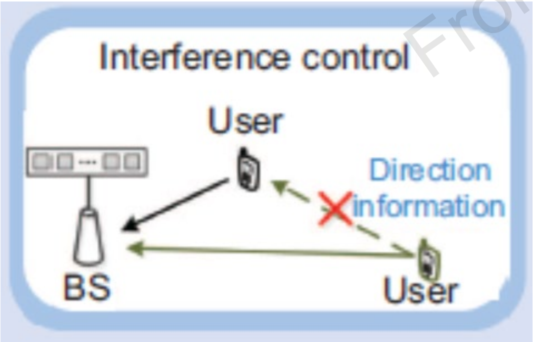
4 Location-assisted mmWave communications (Cont’d)



Feedback location information with some instantaneous channel information supplement can substantially reduce feedback overhead without compromising the data rate.

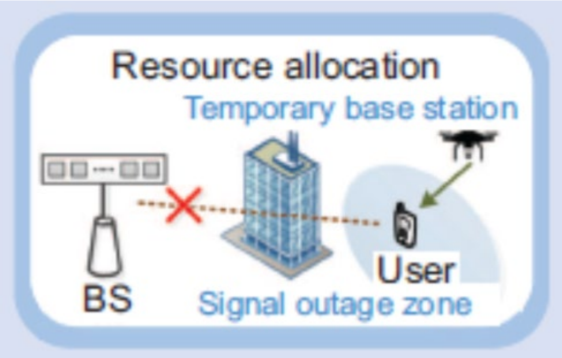


Be aided through a priori location information, which determines the potential window to exploit the synchronization signals from different base stations.

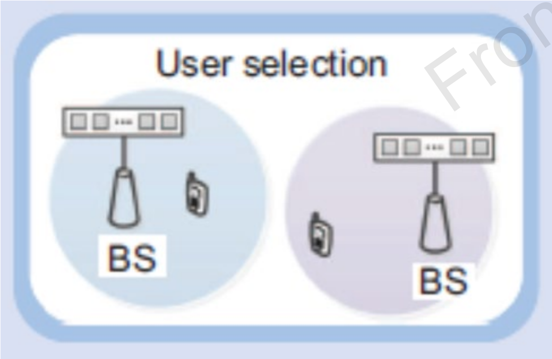


The location of the transceivers also provides useful information about the interference level to be experienced at a specific location, time, and frequency. Hence, the moving user can accordingly adjust the transmission power, frequency, or beam direction to reduce interference from other users.

4 Location-assisted mmWave communications (Cont'd)

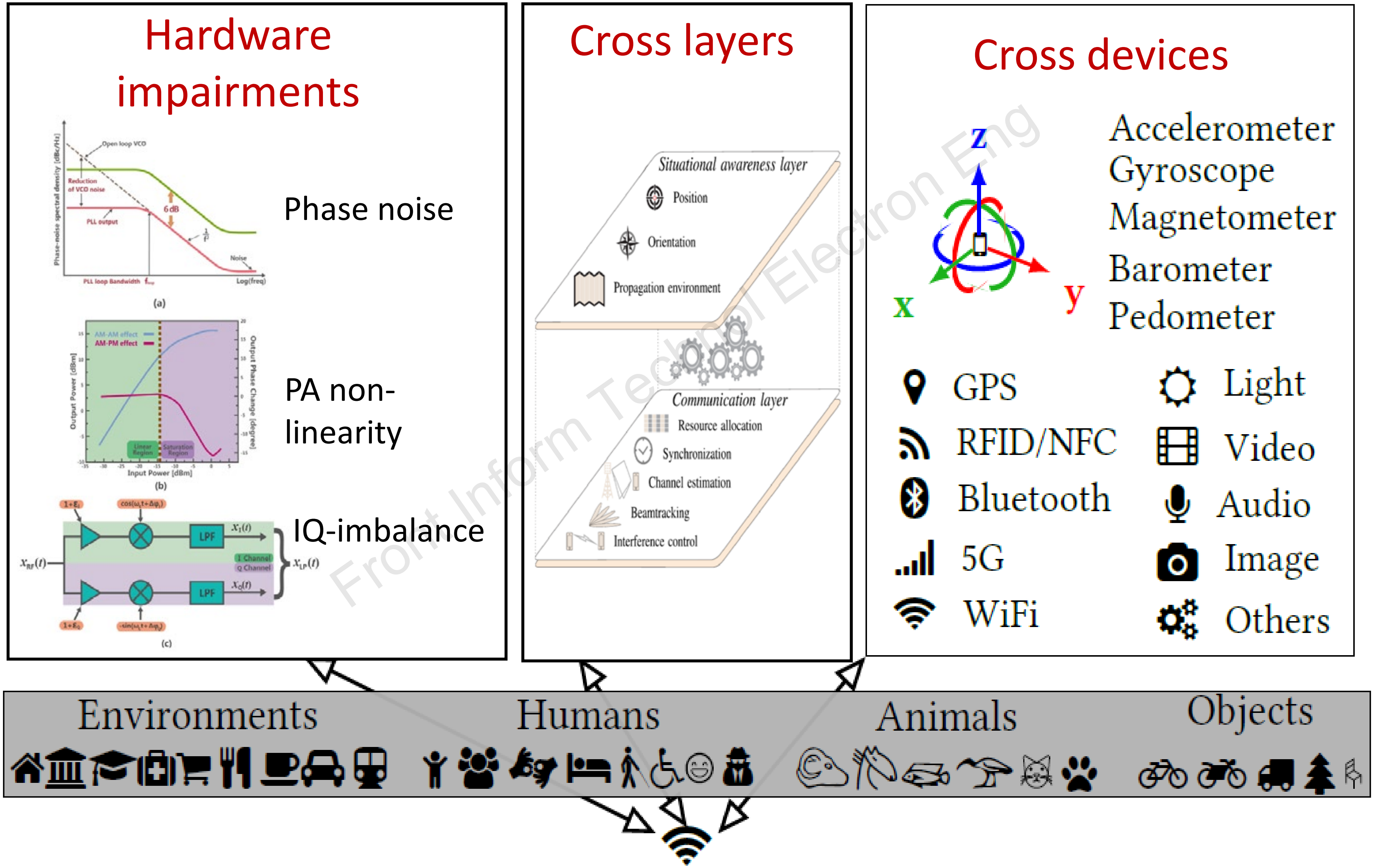


The channel capacity and outage can be predicted using the spatial movement coherence in combination with location and channel prediction. The communication rate is adapted to avoid exceeding the predicted capacity, or extra spectrum resources can be pre-allocated to support the unexpected surge of communication traffic demand. Temporary base stations can also be used to provide communication links in unfavorable signal outage zones.



The easiest way is allowing the base stations to make decisions based solely on the users' locations. Future trends will consider the terrains and layout of blockages, enabling the users to avoid or escape from unfavorable signal dead zones.

5 Future trends



5 Future trends (Cont'd)

Hardware impairments	• At the mmWave frequency bands, risks of increased phase noise and non-linearity of communication systems exist • The uniqueness of the hardware impairments of each device can also be used for identification, thereby turning waste into wealth
Cross layers	• The communication layer or localization layer is currently studied separately • Novel waveform designs • Dynamic medium-access control protocols • Radio resource management algorithms • Information sharing mechanisms
Cross devices	• Single technology cannot currently meet the requirements of ubiquitous communications, high-resolution localization, and energy efficiency of future cellular networks • Multi-domain information fusion from mmWave networks, sub-6 GHz networks, sensor networks, wireless local area networks (WLANs), satellites, unmanned aerial vehicles (UAVs), and radar • Interference management and cancellation techniques