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# Multidevice Interaction

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*As embedded computers of all shapes and sizes are connected to the Internet en masse, the opportunity to exploit their combined capabilities and power is an attractive engineering challenge. Working out the kinks associated with heterogeneous data, lack of standardization, and interoperability challenges will enable an entirely new computing paradigm.*

As unprecedented numbers of computing devices come online to support our day-to-day tasks, it is not uncommon for each of us to own multiple devices to handle various areas of activity. Such devices can have different capabilities and I/O modalities. In addition, we might use specific devices for particular activities (for example, having a work computer and a personal computer), or we might own devices that are solely dedicated to particular tasks (such as e-readers, gaming devices, or networked appliances).

If a device has an embedded processor and is connected to the Internet through Wi-Fi or a cellular network, it falls into the Internet of Things (IoT) category. As this trend further expands our use of computation and provides a wide range of developer opportunities, it will transform traditional "dumb" devices into much smarter and more ubiquitous devices in the future.

## SYSTEM DYNAMICS

Because of the network effect of connecting these devices, a latent and largely untapped value proposition exists for all of this computation, which can be summarized by the term *multidevice interaction*—the focus of this special issue. Collectively, proximate devices can work together in unique ways and provide an improved user experience and greater computing capabilities over what any single device might achieve independently.

Multidevice interaction broadly encompasses two ways in which individual system components can work together to create a whole that is more than the sum of its parts. First, heterogeneous systems can augment one another's capabilities by sharing resources that would otherwise be unavailable. Second, homogenous systems can enhance efficiency by sharing work and cooperating to more quickly solve complex problems.

### Heterogeneous systems

Heterogeneous systems might individually contain resources or peripherals that others do not have. However, together these individual systems can share and aggregate resources into a more effective federated system. Some of the benefits are power optimization and resource sharing.

**Power optimization.** When several mobile devices are present, it is likely that their battery capacities and energy levels will vary. Some have larger capacities, whereas others are smaller and closer to running out of power. Multidevice interaction can help ensure that a computing task can be carried to completion by dynamically moving computation among a variety of devices to reduce the power impact on any one device.

**Sharing unique physical resources.** Consider a scenario in which one device supports a screen and keyboard but has no microphone, and another possesses a microphone but has no screen or keyboard. Wirelessly connecting the two, when proximate, effectively creates a system that supports voice recognition as well as regular text input. This kind of physical device sharing enables a user interface to be constructed on the fly, adapted to the task at hand, and leveraged to make the best use of each device's capabilities.

> **ADVANCES IN CONNECTIVITY, DISCOVERY, AND SECURITY ARE FORMING THE FOUNDATIONS OF MULTIDEVICE STANDARDS.**

### Homogenous systems

Homogeneous systems can also serve users more effectively by accelerating a task, which typically involves dividing it into smaller pieces and redistributing these among similar peer devices that can work in parallel. Some of the advantages are shared sensing capacity and load balancing.

**Shared sensing.** A distributed set of microphones across multiple devices can better localize and isolate audio sources, providing a better overall user experience. This distributed homogeneous sensing capability increases effectiveness not only through redundancy but also by taking advantage of the different physical placement of devices in space—a key property of IoT systems.

**Load balancing.** Homogeneous computers can perform a particular task on one device as well as another; thus, should that task become a burden for one device, there is an opportunity to disperse elements of that task among the other devices until the computational load is more balanced. This results in greater parallelism and higher processing performance for the entire system.

Multidevice computer systems that utilize these approaches will be able to offer users better and more efficient services, increasing the system's overall utility.

## INTEROPERABILITY OPPORTUNITIES

Distributed programming has always been hard, and ad hoc wireless computing even harder, especially when the computers are embedded in products made by a variety of vendors. One of the great opportunities for multidevice interaction and the IoT is to create standard protocols across products in the ecosystem, which would make components from different sources interoperable, rather than relying on vertically integrated solutions. Many current advances in the realms of connectivity, discovery, and security are beginning to form the foundations of multidevice standards.

Considerable progress has already been made in connectivity standards in the form of wireless protocols such as Wi-Fi and Bluetooth, and they have become ubiquitous across a wide variety of devices. Bluetooth's recent extension to Bluetooth Low Energy (BLE) supports small devices that have low-power, long-lived battery operation


**FIGURE 1.** A typical example of an Internet of Things (IoT) smart-home environment.

requirements (such as environmental sensors) and enables a new category of multidevice interaction. As a result of such standards, modern environments that contain desktops, laptops, smartphones, wearables, and environmental sensors all have the potential to interact and connect to the Internet, either directly or through a gateway device (see Figure 1).

Proximate devices are able to interact opportunistically if they share a common discovery protocol that allows computers to find one another and learn about their respective capabilities. Defining a schema that is universally understood and broad enough to cover all devices and capabilities in the industry is a challenge that has yet to be overcome. However, standards organizations are working on it, and we fully expect our industry to eventually converge on one standard in the future.

Security is a necessity in any networked system and a core foundational component of the IoT. Devices in the IoT not only handle sensitive personal information, but they also possess a wide variety of resources necessary to make secure systems. Ongoing advances in hardware-level security (trusted devices), network security, and data management continue to make the overall ecosystem more secure; however, many challenges remain in terms of addressing new and emerging use cases, as well as numerous other legal and privacy policy considerations.

## IN THIS ISSUE

This special issue features five articles that demonstrate the value and diversity of multidevice interaction opportunities.

In "Collaborative and Energy-Efficient Speech Monitoring on Smart Devices," Jarno Leppänen, Mikko Pelkonen, Haipeng Guo, Samuli Hemminki, Petteri Nurmi, and Sasu Tarkoma describe the Collaborative Energy-Efficient Speech Recognition (CeeSR) system, which is designed to capture the best possible audio stream within a room by opportunistically connecting nearby smartphones and selecting the best-quality audio source for recording. This device/sensor management system also trades off power consumption and sound quality to ensure a balanced operating mode.

In "Swarm-Oriented Programming of Distributed Robot Networks," Carlo Pinciroli and Giovanni Beltrame describe a language construct that is part of a new programming language called Buzz, which enables large collections of robots to cooperate on a task and coordinate their behavior while still allowing specializations for individual robots. The authors provide programming examples and demonstrate how the construct results in reusable functionality.

In "Interdevice Media: Choreographing Content to Maximize Viewer Engagement," Timothy Neate, Matt Jones, and Michael Evans examine the dynamics of watching television while interacting with handheld devices. They explore how content designed for the television and the device can be choreographed to provide a richer and more engaging experience, and they focus on managing the viewer's attention—what works well and what creates problems.

Finally, in "Software Abstractions for Component Interaction in the Internet of Things," Tomas Bures, Frantisek Plasil, Michal Kit, Petr Tuma, and Nicklas Hoch explore an engineering paradigm called the Ensemble-Based Components System (EBCS), designed with abstractions expressive enough to build an IoT ecosystem while handling architectural dynamicity, open-endedness, and self-adaptation.

This issue's "The IoT Connection" column, written by Alexander Kott, Ananthram Swami, and Bruce J. West, provides a perspective on the IoT in military applications. "The Internet of Battle Things" makes the case that the battlefield of the future is an extreme example of the IoT in which controlling, monitoring, and securing

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it from a human perspective presents huge challenges. In particular, the scale and level of interactivity with civilian IoT components creates new attack surfaces that require the development of novel techniques to effectively manage it.

Many multidevice interaction design challenges and benefits stem from their roots in distributed systems. However, modern distributed systems now include wireless protocols, proximate discovery, power management, and human–computer interaction that can extend across multiple devices (for example, display casting), which makes this a very rich area for research and product development. These issues have considerable significance for the IoT and impact many aspects of typical modern life.

We hope you enjoy reading the research contributions presented in the feature articles as well as in the IoT Connection column, which highlights how pervasive multidevice interaction occurs across all professions, even the military.