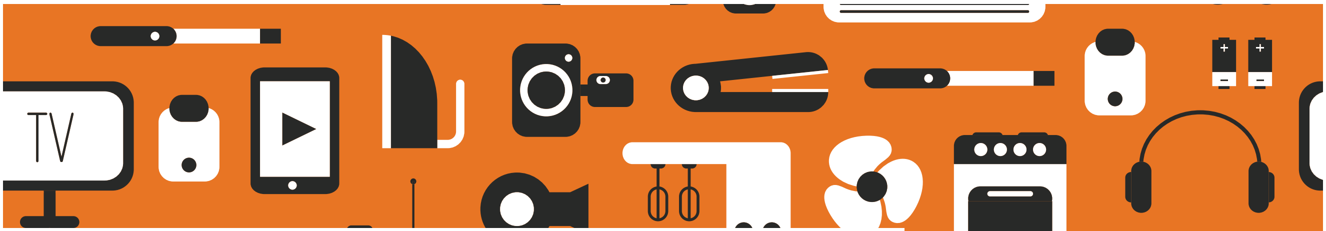
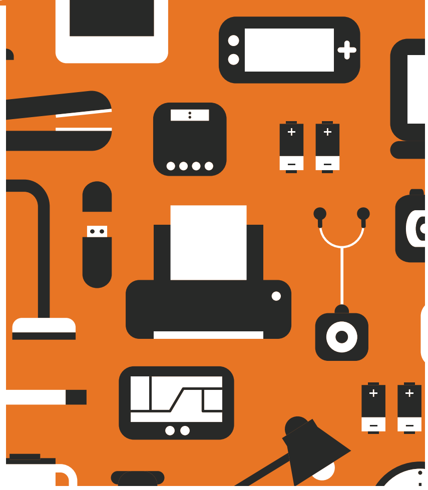


IoT-Based Sensing and Communications Infrastructure for the Fresh Food Supply Chain



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Assisted by centralized data collection and analytics, IoT-based mechanisms can substantially reduce food waste, improve transportation and distribution efficiency, and support quick removal of contaminated or spoiled products from the fresh food supply chain.

FROM THE EDITOR

Discussions about the Internet of Things (IoT) are often focused on the consumer, but the IoT has far greater potential for societal benefit in industrial applications. In this article, the authors highlight the issues surrounding food transport and distribution, and how food spoilage can be mitigated by improved tracking and sensing. Some of the biggest IoT challenges for this industry are maintaining ubiquitous connectivity and sensing the state of food products even in very densely packed environments. *— Roy Want*

Transportation and distribution (T&D) of fresh food is an enormous and growing enterprise due to increasing demand and worldwide sourcing of fresh food. Unfortunately, fresh food T&D not only suffers from significant spoilage and waste but also from dismal efficiency. Here, efficiency is defined as the fraction of T&D capacity that's used. Current T&D efficiency estimates of trucks and trailers are in the 10 to 20 percent range, and food spoilage and waste estimates are in the 12 percent range. Fresh food is easily contaminated, and spoiled or contaminated food is mostly responsible for foodborne illnesses that affect 48 million people annually in the US alone.

Supply-chain logistics is transforming because of the current trend of outsourcing operations to a shared third party, or third-party logistics (3PL).[1] Shared logistics is further assisted by several Internet of Things

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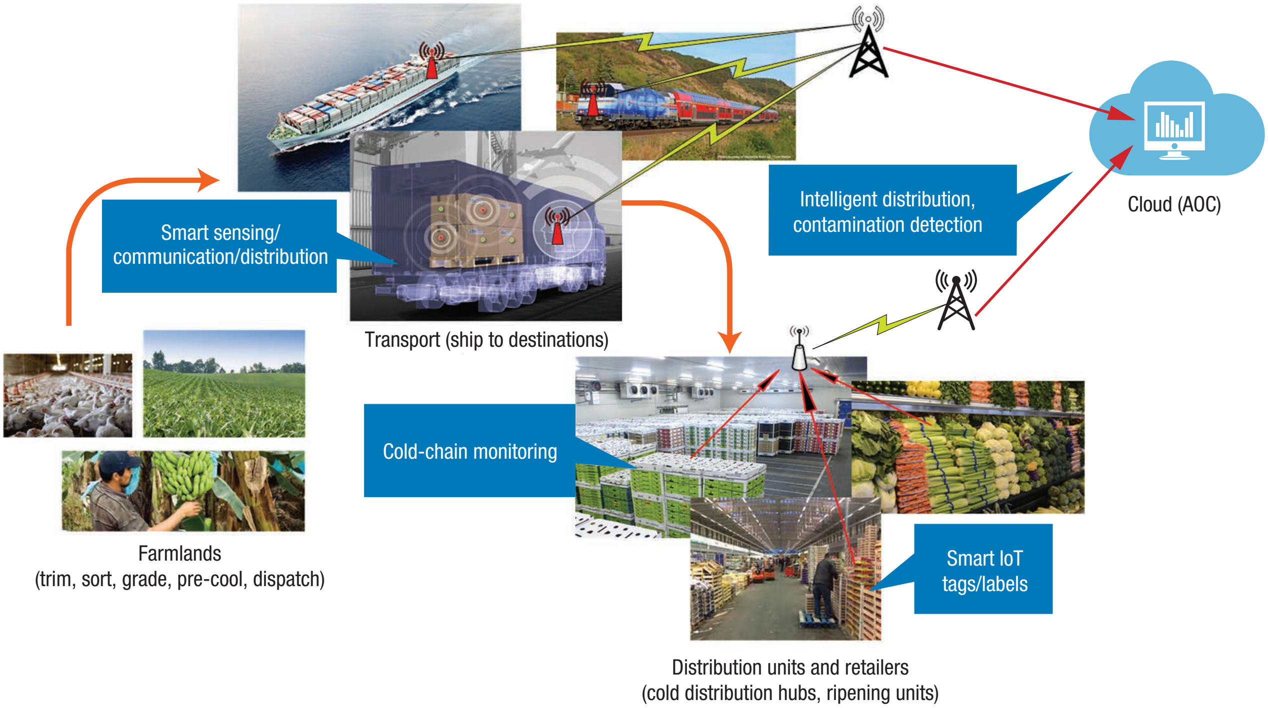

Figure 1. Sensing and communications (S&C) architecture in a fresh food supply chain. AOC: analytics and operations center.

(IoT)–based solutions, such as GS1 standard–based RFID labeling of facilities, locations, products, packages, and carriers. These solutions—along with sensing and communications technologies—enable intelligent T&D. The Physical Internet—an open global logistics system founded on physical, digital, and operational interconnectivity[2]—encompasses many of these ideas and applies concepts from Internet data transfer to real-world shipping processes. We have extended these concepts to fresh food logistics,[3] demonstrating several similarities to computer networks.[4]

The critical problem with transporting fresh food is the deterioration in quality over time while it passes through the T&D pipeline and is subjected to different temperatures, humidity levels, vibrations, and so on. This exposure affects the product in multiple ways, including the attributes detected by the customers (color, texture, odor, firmness, and taste) and latent parameters such as vitamin and bacterial content or chemical changes.

Although T&D pipelines already include some level of temperature and quality monitoring at intermediate points, in this article we discuss a fine-grained, continuous monitoring of the products' quality. Assisted by centralized data collection and analytics, our proposed mechanisms can substantially reduce food waste, improve T&D efficiency, and support quick removal of contaminated or spoiled food from the supply chain.

QUALITY-SENSING TECHNOLOGIES

Food sensors embedded in intelligent packaging provide a quality indicator to both retailers and customers. A simple form of smart packaging is the use of labels—such as a time-temperature indicator (TTI)—that show the accumulated time-temperature history of a product. More sophisticated indicator sensors are used to analyze food quality by monitoring different organic compounds, ethanol, glucose, or gas molecules, which usually transform the indicator with a color-change response. For example, volatile amines in fish can be sensed via a commercial tag.[5] Sensors with other functionalities include those measuring bacterial content, contamination, texture or color degradation, bruising, and so on. Simple sensors are beginning to show up, such as C2Sense, FoodScan, and the Salmonella Sensing System.[6]

To allow such sensors to continuously monitor and report on food quality, we propose to combine them with a radio. Such an integrated sensing and communications (S&C) module can be embedded in each package within a box, making it possible to perform

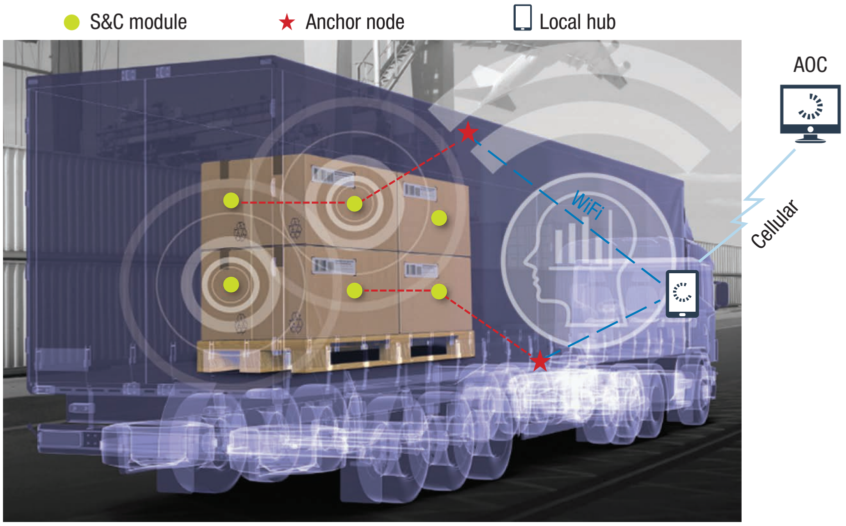

Figure 2. Food quality sensing and communications inside a truck. The communications infrastructure consists of long, medium, and short-range communications.

online data collection and analytics, and thereby take timely remedial actions. These actions could take many forms, including rescheduling deliveries so that deteriorating food is distributed locally to retailers or food kitchens; reprioritizing transport, loading, and unloading schedules based on product quality; and removing contaminated or spoiled product immediately to avoid carrying it further. The overall architecture is depicted in Figure 1.

COMMUNICATIONS INFRASTRUCTURE FOR ONLINE TRACKING

T&D operations typically use several levels of packaging, from a customer-bought package to large pallets transported on trucks or stored in a warehouse. Considering a retailer as the end point of the T&D pipeline, our interest is in a retail-level box containing the S&C module. These boxes can then be put together into pallets that are handled by the T&D pipeline. The S&C module can monitor the content using a contact (chemical) or non-contact (gas sampling or imaging) sensor. The S&C modules can be removed and returned by the endpoint (such as a retailer) to the shipper or processing plant via regular reverse logistics, allowing for more sophisticated sensors than in a throw-away packaging solution. Given automation and extensive GS1-based RFID labeling, it's possible to record the box or pallet order and RFID during palletization and loading/unloading. Thus, a correspondence between a box's location and its RFID can be established.

The radio in the S&C module supports both data collection and box localization. The latter is essential so the data can be tagged with the box's location. We assume that the S&C module is packed in roughly the same position in each box, and thus can be used to estimate the relative location of the box via a localization procedure.[7] This is done whenever a pallet is loaded on a carrier or stored in a warehouse equipped with the proposed anchors and communications infrastructure. The relative location supplied by the S&C module can be used along with the RFID versus the loading order map discussed above to identify the box RFID from which the S&C is sending the data.

Figure 2 shows the overall architecture with one S&C module per box. The boxes are part of a pallet, and multiple such pallets could be transported by a carrier or stored in a warehouse. Each carrier or warehouse has a local hub that provides long-range (LR) communication on the back end (for example, cellular) to enable data transfer to an analytics and operations center (AOC), which could be cloud-hosted. The AOC receives data periodically from all active carriers and warehouses (including empty ones) operated by the 3PL in its entire network so that it has a global view of operations and resources. The centralized availability of sensed quality, contamination, and localization information at the AOC from the entire T&D network has the potential to revolutionize logistics operations, particularly when coupled with ongoing automation trends.

Within each carrier or warehouse, we need a local network to transmit data from individual S&C modules to the local hub. This involves two types of communications: medium range (MR) and short range (SR). MR technology is required for communications across rail cars, sections of a ship, warehouse rooms, one end of a truck to another, and so on. Wi-Fi is an obvious choice here, but other technologies can also be used. SR technology is needed to communicate across S&C modules in a pallet or across closely spaced pallets. We found that RF isn't appropriate for SR communications, so we instead make a case for magnetic induction (MI)–based communications, which we will discuss next. We assume a set of anchor nodes deployed in the vicinity of the pallets (for example, on the carrier or warehouse walls), which provide dual MR/SR interfaces to enable the transmission of S&C data over the local network. Finally, the local hub has an MR interface on the front end to provide MR/LR linkage. Figure 2 illustrates the three types of communications.

COMMUNICATIONS TECHNOLOGIES FOR S&C MODULES

The S&C modules need to operate in a unique environment of very densely packed radios with the signal propagating through the aqueous/tissue media of fresh food. The typical industrial, scientific, and medical (ISM) RF communications, such as Bluetooth in the 2.4 GHz ISM band, don't work very well in this environment due to high signal absorption and complex channel conditions. For example, research in a similar context of body-area networks shows a path loss of 20 to 60 dB at 10 cm for 0.1 to 1.0 GHz radios.[8] Reducing absorption by choosing lower frequencies (for example, 802.11 ah) helps in attenuation, but would require larger antennas and cause severe interference in this very dense sensor environment.

There are two other prominent communications technologies to consider for this purpose. The first is ultrasonic communication.[9] However, ultrasound propagation in tissues is affected by multipath fading because of the inhomogeneous density and varying sound velocity. The arrival of multiple attenuated and delayed versions of the transmitted signal at the receiver makes detection and decoding very challenging. Ultrasound absorption can also lead to heat generation, which is undesirable for perishable food.

The second alternative is MI-based communication in the high-frequency band (3–30 MHz). This technology exploits resonant inductive coupling (RIC) between two matched coils, each forming an LC circuit with the same resonance frequency. RIC has been used successfully for extremely efficient power transfer over short distances, and is used for contactless mobile phone charging and car battery charging. MI communication modulates the magnetic field and forms the basis of near-field communication (NFC). It is mostly unaffected by the tissue medium[10] and can work at much lower power levels than RF and ultrasound over short distances. The MI channels are also more determined as the MI signals are not reflected or scattered by the surrounding environment, and thus suffer from smaller signal fluctuations and multipath effects. Also, there is no known biological effect of MI in the food or tissue medium. A 5 cm diameter coil can provide an adequate range for our application.[7]

The magnetic coupling between two coils depends on their relative orientations, and the energy transfer between them attenuates with cosine function of distance. However, it is possible to achieve a near-isotropic transmission with a tri-directional coil antenna.

DATA COLLECTION AND ANALYTICS

As previously discussed, each box will contain the S&C module, which not only results in a very dense radio environment but also requires multihop communications to send the food-quality data from any arbitrary box to the local hub. The simulation-based analysis in our previous work[7] indicates that this should be workable; we are currently building a few S&C modules to study various real-world communications issues. One aspect that would also need to be considered in a real-life deployment is the distortion of the magnetic field due to ferromagnetic materials such as the walls or floor of a truck.

The S&C modules would likely use small coin-cell batteries, and it's highly desirable for such a battery to last many years.[7] Fortunately, the data collection needs of this environment are very modest—it suffices to sense and transmit food-quality data every 30 minutes. Thus, all modules can be kept in a deep sleep mode except during periodic data-collection phases when each module wakes up according to a fixed schedule, collects and transmits its data (along with its relative location) to a neighbor, and goes back to sleep. By starting with the innermost modules in the pallet and moving toward outer ones that are closer to the anchor nodes, it's easy to devise a simple store and forward mechanism to push data from each S&C module to an anchor via MI communications, and from there to the local hub over Wi-Fi.

A ubiquitous deployment of such an infrastructure would allow extensive data analytics at the AOC, both for supporting the logistics operations in real time and for improving them via offline analysis of past data. Here, we discuss a few applications enabled by these capabilities.

Intelligent distribution

Warehouses and distribution centers typically use a first in, first out (FIFO) distribution policy to determine which pallets to ship next, which is based on the false assumption that all pallets have been handled the same way, and thus the oldest pallets have the shortest shelf life and should be sent first. A smarter and more efficient approach is to enable a first expired, first out (FEFO) approach by using the more accurate shelf-life estimation from the online sensing infrastructure. A much better distribution strategy can be achieved by matching the remaining shelf life of each package to the transit time and consumption rate of each destination. Other policies might also be useful in specific cases, such as a freshest product first (FPF) policy when the product value goes down rapidly with quality. However, differing contracts relating to freshness requirements could make this very challenging.

Proactive contamination detection

Tracing the source of contamination or food-borne illness is very involved in a large food chain; however, the architecture in Figure 1 coupled with logistics automation can provide two key benefits: proactive monitoring of contamination and associated removal of contaminated food from the supply chain, and the ability to narrow down the potential sources of reported food-borne illness or contamination.

Ambient control

Current logistics operations follow fixed guidelines in the use of pre-cooling and cooling during transport and storage. A proactive, fine-grained quality-monitoring scheme allows for optimization in cooling based on the current condition of the products, predictions of quality deterioration in the future, expected transit time, the realizable monetary value of the product, cooling costs, and so on. The centralized availability of data at the AOC from all carriers and warehouses used by the logistics operator allows for many data-driven continuous optimization opportunities. These can be based on both historical and current data for the same or similar products and conditions. Furthermore, it becomes feasible to address the joint problem of optimizing both cooling and delivery rescheduling to minimize waste and cost.

LOOKING AHEAD

Our integrated IoT-based online monitoring approach using smart logistics can address the critical needs of reducing food waste, increasing transportation efficiency, and tracking food contamination. The emerging MI-based communications technology appears well suited for local communications in this environment; however, there are several challenges to making the technology work reliably in the highly dense and dynamic environment of real-world logistics operations. Further advances are needed to derive actionable intelligence from the collected data in real-world conditions, such as the presence of faulty modules or patchy cellular communications. Real-world logistics operations also have other complexities that make flexible distribution challenging, such as delivery contracts, party-specific distribution policies, and specific data-privacy needs. We hope this article will spur further research and result in solutions to many of these issues. C

REFERENCES

1. R. Leuschner et al., "Third-Party Logistics: A Meta-Analytic Review and Investigation of its Impact on Performance," *J. Supply Chain Management*, vol. 50, 2014, pp. 21–43.
2. B. Montreuil, "Towards a Physical Internet: Meeting the Global Logistics Sustainability Grand Challenge," *Logistics Research*, vol. 3, nos. 2–3, 2011, pp. 71–87.
3. A. Pal and K. Kant, "A Food Transportation Framework for an Efficient and Worker-Friendly Fresh Food Physical Internet," *Logistics*, vol. 1, no. 2, 2017; www.mdpi.com/2305-6290/1/2/10.
4. K. Kant and A. Pal, "Internet of Perishable Logistics," *IEEE Internet Computing*, vol. 21, no. 1, 2017, pp. 22–31.
5. J.P. Kerry, "New Packaging Technologies, Materials, and Formats for Fast-Moving Consumer Products," *Innovations in Food Packaging*, 2nd ed., J. Han, ed., Academic Press, 2013, pp. 549–584.
6. "Salmonella Sensing System: New Approach to Detecting Food Contamination Enables Real-Time Testing," Phys.org, 18 Oct. 2013; phys.org/news/2013-10-salmonella-approach-food-contamination-enables.html.
7. A. Pal and K. Kant, "Magnetic Induction Based Sensing and Localization for Fresh Food Logistics," *Proc. IEEE 42nd Conf. Local Computer Networks* (LCN 17), 2017, pp. 383–391.
8. D. Werber, A. Schwentner, and E.M. Biebl, "Investigation of RF Transmission Properties of Human Tissues," *Advances in Radio Science*, vol. 4, 2006, pp. 357–360.
9. G.E. Santagati and T. Melodia, "Experimental Evaluation of Impulsive Ultrasonic Intra-Body Communications for Implantable Biomedical Devices," *IEEE Trans. Mobile Computing*, vol. 16, no. 2, 2016, pp. 367–380.
10. M. Masihpour, D. Franklin, and M. Abolhasan, "Multihop Relay Techniques for Communication Range Extension in Near-Field Magnetic Induction Communication Systems," *J. Networks*, vol. 8, no. 5, 2013, pp. 999–1011.

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