Digitalisation in Shopping: An IoT and Smart Applications Perspective

Oliver Cvetkovski, Panagiotis Gkikopoulos and Josef Spillner

Abstract With online shopping gaining in convenience and coverage, physical shopping is under pressure to innovate. Consequently, smart shopping concepts based on digitalisation are increasingly explored and piloted in urban and rural environments. Beacons lure in customers with push messages and guide their path to desired products in the shops. Doors open automatically for eligible shoppers. Electronic shelf labels are able to adjust prices depending on external factors such as weather and shopping trends. Automated basket scanning and new forms of payment complete the changing experience. Restocking and floor cleaning robots are making inroads. Hence, innovative solutions for smart shopping combine the Internet of Things (IoT) and cyber-physical systems (CPS), and require an appropriate research infrastructure for further exploration. This chapter describes the experience with the IoT/CPS-focused smart shopping lab environment at Zurich University of Applied Sciences and discusses the software and networking design of smart applications in this domain, such as social shopping and product navigation apps, as well as ongoing research challenges.

Key words: Smart City, Smart Shopping, Internet of Things, Cyber-Physical Systems, Real-Time Location Services

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1 Introduction

Smart cities and regions have been a visionary application domain for computer science and engineering for several years. Since the late 2010s and early 2020s, even mid-sized cities have been adopting concepts of technology-supported smartness on a broad and strategic basis. City planners, officials and even private actors in the public space are facing the need to structure their activities and set priorities to cater more smartly to human demands. Fig. 1 shows the commonly used smart city wheel that breaks down the activities into more fine-grained topics around smartness. That smartness is often enabled by emerging hardware and software technology and yet would bring real value for citizens, businesses and other city actors. Thus, investigating the practical value of technology becomes an essential task for researchers to contribute to this value creation. Topics in smart cities benefiting from new technological approaches include smart mobility, smart living, smart economy and others, which can then be further broken down to concrete realisations such as smart buildings or smart vehicle sharing.

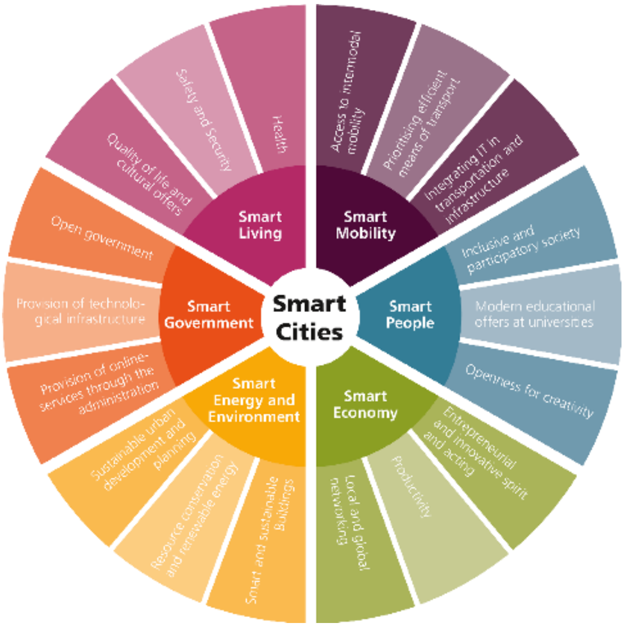


Fig. 1 Smart city wheel reproduced from [1]

Nevertheless, despite trade and commerce being one of the key drivers behind the creation and proliferation of cities ever since the origins of civilisation, smart shopping concepts have not been as prominent as other topics in the context of research on smart cities and regions. At its core, smart shopping is mainly located in the smart economy sector of the wheel, but also touches on smart living and smart mobility and potentially other sectors. It acknowledges the need to innovate for convenience to be able to compete with the rise of online shopping, which in Switzerland alone surpasses 15 billion Swiss francs annually [2], while maintaining the quality of life factors for cities. With emphasis on people-centric smartness, smart shopping specifically refers to the ability of consumers to maximise the convenience, efficiency and safety in obtaining goods or services at any time and at any place. The term place is meant to be cyber-physical, blurring the distinction between the physical world and online services. Hence, smart shopping requires the complementation of online shops and existing physical stores with technology-supported stores that connect to the consumer's devices as clients to on-device and online services. Such technology, if designed and implemented properly, can speed up the shopping process while retaining the advantages of physical stores in local tax generation, anonymity, sustainability and decentralised innovation. Evidently, the supporting technology itself then should be cyber-physical, lending to an advancement of concepts around IoT and CPS as an interface between software and the world, as well as multi-modal human-computer interfaces (HCI).

Industry progress around isolated smart shopping trials within city areas has become visible but is not yet well understood, especially concerning its potential to integrate into a city-wide smart shopping experience that also covers smaller shops, but also concerning technological limitations and further opportunities. Examples from individual chains include cashierless stores as known from Amazon Go or Avec Box [3], and e-commerce integration for Point-Of-Sale (POS) to unify physical and online purchases in so-called cross-channel and omni-channel sales [4]. This cyber-physical combination has seen raising prominence during the COVID-19 pandemic with terms such as click-and-collect or click-and-meet [5]. Another consumer-facing example is the Snäx disposer for convenience food at workplaces that is opened with a mobile application based on a QR code, and billed based on products taken out. In contrast, a smart store management example is the Ubica scan robot to regularly produce digital twins of shops that resulted from the European research project REFILLS [6, 7]. A thorough analysis of such industrial trends is therefore mandatory in order to identify knowledge gaps and research questions, and in order to think about the further advancement of such technologies with human needs and preferences across cities and regions in mind. An extended scope that considers also the outdoor experience in the physical world and the associated network communication between devices and humans is therefore necessary.

In this book chapter, the custom-built IoT/CPS research infrastructure and the early-stage research experience on smart shopping [8] at Zurich University of Applied Sciences is summarily described and presented to the reader. The focus is on the underlying devices and network topologies of the smart shopping lab, as well as on smart applications which guide the stakeholders including consumer and store owner, combining three places: online, physical outdoors, and physical indoors. Due to the emergence of the application domain and the associated research field, the ambition of the chapter is not to present well-founded theories. Rather, we hope that the reader will develop a broad understanding of the domain and of applied research methods to advance the state of technology in it, and is subsequently able to study further literature that focuses on narrow problems.

2 Goals, technology support and challenges

2.1 Smart shopping goals

As outlined before, smart shopping shall enable consumers to more efficiently and conveniently obtain products and services, in particular when nearby opportunities arise embedded into ongoing activities such as sightseeing, commuting or eating out. The confirmation of an opportunity can be based on various factors, ranging from knowledge of the consumer needs to massive price reduction. To be effective, the process often needs to start at an earlier point, converting potential customers into actual customers through the advertisement of valuable information, offers and opportunities. There are in fact even more stakeholders involved beyond the potential consumers and actual consumers when considering smart shopping processes holistically.

The two main groups in focus for a goal and technology analysis are store owners, selling products in physical stores on behalf of the producers, and consumers, interested in purchasing these products and thus acting as clients and customers in these stores. Both need to be connected by a shared vocabulary and common understanding of the naming, availability, pricing and pickup/delivery modalities of products. Likewise, both represent certain subgroups including prospective customers, or future store owners looking for a suitable place to open their shop. Further stakeholders involve city planners looking for more bustling downtowns (usually translating into more sales tax income), city traffic planners getting more data points to plan logistics infrastructure, and suppliers wanting to optimise their respective shipments to store owners.

The main goal of a consumer is then to get all desired products in a short amount of time, at a low price and without obstacles such as overrun shops (with long checkout queues) or items being out of stock, including by emergent rebound effects or paradoxons known from other crowd navigation systems [9]. This may lead to a combination of store visits, or even a combination of physical and online processes, rather than just being confined to a single store. The main goal of the store owner is to sell as much as possible, even products that the consumer may not have had on the shopping list beforehand. A goal conflict is imminent. It could be resolved by targeting different groups of consumers who explicitly and dynamically select their preferences in terms of wanting to see additional offers or not. Nevertheless, there may also be shared goals, such as a store owner wanting to empty their stock of a particular kind, and being able to advertise special offers; or a store owner offering regionally produced products that a certain segment of customers is keen on buying.

2.2 Technology support

Smart shopping is enabled by different technologies and data sources depending on the target group, primarily consumers and store owners. It is inherently data-driven, with part of the data being acquired from the real world by sensing and signalling, and part of the data being input by users from the aforementioned target groups. Fig. 2 shows a schematic view of selected smart shopping processes and enabling technologies, thereby relating target groups, data sources and the digital support for smart shopping processes enabled by them.

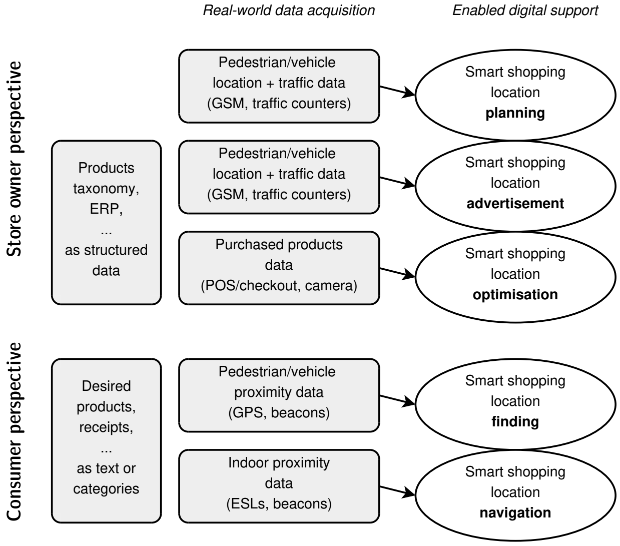


Fig. 2 IoT and real world data acquisition perspective on smart shopping processes; non-exhaustive selection

From a technology and data perspective, smart shopping thus involves the following components and processes:

- Planning: Analysis of pedestrian (prospective customer) frequency in any area, along with existing offerings, to determine optimal placement of new shops with attractive product and service portfolios. This information is generally available from mobile phone operators, given the ubiquity of phones, but also increasingly from urban traffic sensing and public transport operators.
- Generic Advertisement: Information about offered products and services, as well as procurement channels, to interested persons independently from their location. This information is typically reflected in websites, apps and e-commerce shops, based on product management databases and inventory systems, but can also be broadcast to the physical world through beacon signals.
- Specific Advertisement: Attracting pedestrians and other nearby persons to stores in real time, using real-time location services (RTLS). As technological foundation to determine proximity, Bluetooth Low Energy (BLE) beacons and WiFi access points (APs) can be used in addition to Global Navigation Satellite Systems (GNSS) such as GPS or Galileo. For social shopping based on crowd recommendations, the detection of nearby users via their mobile devices based on BLE becomes another option.
- Finding: Matching information about desired products and services. The matching can be performed through various algorithms depending on the data representation, ranging from structured to unstructured (text, voice) input from the human side.
- Navigation: Electronic shelf labels (ESLs) based on LCD or e-ink displays. Inside the store, dozens of ESLs per square meter are able to communicate through protocols such as BLE. Due to their fixed position, they can be used to aid navigation, but also to generate attention through display interaction.
- Optimisation: Smart baskets. When a consumer takes a product from a shelf, either a camera or a weight sensor at checkout time determines the products carried in a basket. This information can be used to verify the shopping process and to generate recommendations before leaving the shop.

2.3 Technological challenges

There are several challenges associated with these processes, both on the hardware side and on the software side. While pure functional engineering is often possible, the challenges emerge from the desire to gain holistic solutions that take human preferences such as convenience, privacy preservation, social interaction and low environmental footprint into account. Four of these challenges shall be presented briefly, along with corresponding research fields across computer science and engineering:

1. ESL and beacon operation and communication. Low-maintenance and energy-efficient operations are essential to operate smart shopping at scale. New trends in hardware encompass energy harvesting and solar-powered devices such as ESLs and beacons, as well as complete suspend mode apart from scheduled communication slots. How to configure the physical deployment of devices and their configuration is not yet well explored. Innovative ideas encompass the semi-automated registration of ESL positions according to base data from a Building Information Model (BIM) that describes the room properties including floor, wall and ceiling materials, and the resilient transmission of offers through Bluetooth payload without requiring a working Internet connection on consumer devices despite TCP/IP being likely the most widely activated option.
2. Precise determination of proximity. The trade-off between price and precision is well understood and also applies in the improvement of heuristic metrics, such as distance between a device and a signal, by running trilateration, averaging or voting algorithms over a set of signals. The challenge is further complicated by the use of heterogeneous devices such as access points (AP), BLE/ESL devices, and mobile phones or smart watches representing the user position. For instance, sometimes WiFi-based trilateration might be the only option but at reduced precision.
3. Product capturing. Object identification based on training data acquired via Machine Learning (ML) and image segmentation without training are the two primary methods to let store owners take photos of product shelves and rapidly feed them in structured form with price information into an offerings database. If available, offers can be extracted from Enterprise Resource Planning (ERP) databases, in particular when quantity information can be inferred dynamically from modern POS with ERP connectivity.
4. Product matching. Users enter their desired products via voice, in free text form, or by browsing categories. Methods such as Speech-To-Text (STT) and Natural Language Processing (NLP) are required to be able to interpret human input on needed products and to calculate matches against the knowledge of offered products. Users might also have a picture of a favourite product from a trip to another country and look for specialised shops nearby that offer that product, leading to an object detection method. In addition to 1:1 matching, 1:n matching might be performed, for instance based on cooking recipes that require several ingredients from a supermarket, or based on office setup plans that require different devices and cables from a tech shop.

Further challenges such as privacy-preserving recommender systems based on the purchasing behaviour of consumers or crowd campaigns against food-waste are emerging and should be dealt with by researchers in the coming years.

3 Research infrastructure

In order to solve the research challenges and drive technological progress, Zurich University of Applied Sciences has set up a smart shopping lab as a research infrastructure and is partnering with stakeholders such as cities, city vendor associations, store operators and technology providers on this basis. This cyber-physical constellation, consisting of both the physical infrastructure and the software prototypes running interactively or as background services, forms one of the world's first 'smart shopping'-focused research and innovation collaborations and contributes to the refinement of technology-based smart city concepts through research work and student projects.

3.1 Physical infrastructure

Following a real-lab [10] approach, an exemplary smart shopping lab shelf has been set up to host sample products along with technological support to acquire them. Pictured in Fig. 3, it carries several beacons and ESLs along with further communication and edge computation hardware such as a BLE-capable AP. Additionally, tablets and smartphones are available for interactive demonstrations along two paths, one for the store owner (e.g. to capture new products, check the inventory or process customer service requests) and one for the consumer or prospective consumer. To communicate research results, QR codes provide links to further resources such as publications or download links. Researchers with interest in innovative hardware, such as solar-powered ESLs, can use the shelf as a suitable testbed for their ideas.

The connectivity between the individual things and devices is a key concern of the research infrastructure. Apart from a regular WiFi, a specific authentication-less IoT WiFi is available for registered MAC addresses. Several Bluetooth wireless communication versions can be compared: 4.0 (introduction of BLE), 4.1 (introduction of peer-to-peer communication with flexible client/server roles), 4.2 (compressed transmission), 5.0 (higher distances up to 100 metres), and 5.1 (direction finding). Especially the BLE 5.1+ features such as centimetre-level direction detection [11] are promising towards future application designs, but require more time to propagate into affordable devices.

3.2 Software architecture and topology

A complex cyber-physical domain like smart shopping requires being modelled and implemented as a capable distributed system to function effectively.

Fig. 3 Smart shopping lab shelf

The system architecture spans across hardware including a mobile device for signal discovery and user interactions, beacons and ESLs emitting signals, WiFi access points allowing communication and thus also emitting signals, and backend services deployed at the edge (i.e. on a programmable AP) or on dedicated servers. Moreover, it encompasses software for product identification and search, product and shopping list specification, location and proximity determination, and route calculation for complex shopping lists. Hence, it is inherently a distributed system and as such concerned with coverage area, reliability and performance among other relevant metrics. Fig. 4 summarises the distributed software architecture and highlights the network topology between the components to permit communication and messaging between the distributed system components.

3.3 Software applications

Two prototypical software applications for use on mobile devices have been created to support demonstration paths for store owners and consumers, as well as further research. The applications are coupled but could also be deployed standalone in production.

Fig. 5 shows the prototype of the consumer-facing application. Consumers look for products or define their shopping lists. They can enter full-text information and/or select from a number of pre-defined tags following standard product taxonomies, which are for instance derived from the ERP. The input modality could be extended to capture voice, recipes and so forth in order to extract tags automatically. All inputs are either stored on the consumer's mo-

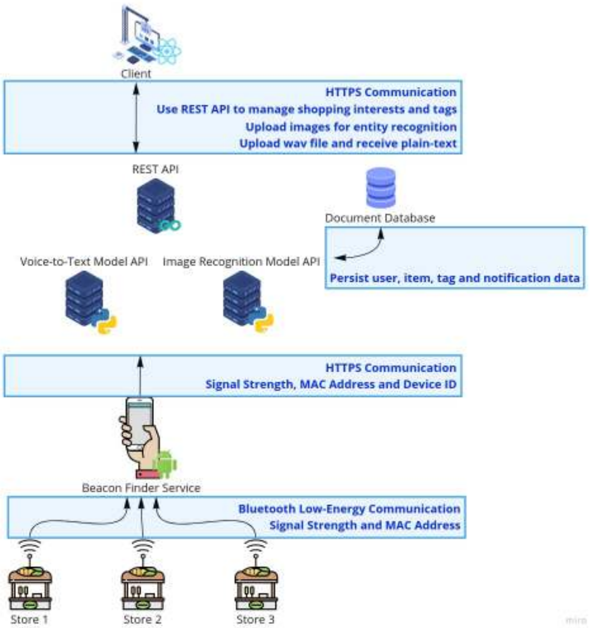
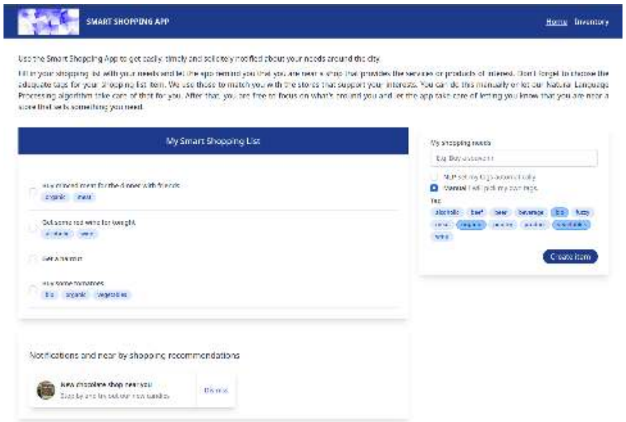


Fig. 4 Smart shopping software architecture and communication topology

bile device or, if network connectivity is provided, in a networked database, complementing shop and product position data. At the bottom, a notification area informs the consumers about being in proximity to a store or shelf carrying a matching needed product. This functionality can be triggered based on GNSS, WiFi or BLE proximity. Hence, depending on the needs concerning resilience and self-sufficiency, as well as operational constraints, the application can be implemented to work in centralised or decentralised mode. For the prototype, the centralised implementation with BLE triggering has been chosen, rendering the mobile device into a stateless part of the system.

In contrast, Fig. 6 shows the store owner perspective. Store owners define the tags and create the inventory of products based on photos taken directly from within the application. Each item is curated with at least a name and a price, and potentially a number of tags relating to a taxonomy. Moreover, any deployed beacons can be associated to represent the shop, the shelf or the product itself in the physical world, providing the link to the consumer-facing application by describing the object's physical boundaries as well as further characteristics, such as the product tags, name and price.

Not every potential consumer would however install an application only for shopping in a particular city or region, especially when spending little time there as a tourist or business traveller. With this adoption constraint is mind, further interaction concepts such as integration of the functionality



Notifications and near by shopping recommendations

Fig. 5 Smart shopping mobile app prototype, consumer perspective

This view is limited to store owners.

Choose an image to be processed

No file chosen

Recognised products

Fig. 6 Smart shopping mobile app prototype, shop owner perspective

into commonly used tourist applications, or even physical infopoints for basic needs of visitors, are being investigated based on the existing prototype.

4 Proximity Experiment and Findings

As explained, the research infrastructure carries multiple experiments and serves as a real-lab-level validation environment. Due to space constraints, only one of the experiments already conducted will be presented in detail. Its purpose has been the understanding of beacon-based indoor navigation in order to permit more personalised shopping, taking the preferences of customers into account to guide them straight to the desired products.

4.1 Indoor navigation experiment design

Using the research infrastructure for smart shopping, the selected experiment is designed to find answers to the second technological challenge, the precise determination of proximity between a consumer and a product. Specifically, the applied research question guiding the experiment process is: Given the usually unreliable Bluetooth signal strength of beacons, does the multitude and density of ESLs, each of them acting as a beacon, aid in translating signal strength to a reliable distance metric, so that more precise indoor navigation to the target shelf becomes possible? Notably, is the trilateration quality of a line or array of ESLs good enough to be able to avoid a BLE-capable AP as an additional reference point, and thus to reduce the hardware budget? Hence, the experiment investigates a price versus precision question that store owners and their technology partners are confronted with in practice.

Indoor navigation based on wireless communication, sonar or camera feeds or even device sensors has been a research topic for about twenty years [12, 13]. They originate from autonomous and robotic navigation but have increasingly been applied to humans, for instance in emergency guidance. This experiment therefore does not reveal fundamentally new techniques, but outlines how to apply specifically recently investigated methods relying on wireless signal strengths [14, 15, 16] to the domain of smart shopping where beacon signals are available from ESLs.

The experiment does not consider navigating to the right level of the shelf or the right product itself, which is however also not necessary due to the ability of ESLs to signal the right destination on the display itself or appropriate photos being shown on the mobile device. The signalling of the successful end of the navigation, in particular in crowded environments, is a human-computer interface concern and would warrant separate research. Hence, the research problem can be considered solved if the consumer steps in front of the correct shelf and rapidly gets to select the right product based on that additional signalling. Fig. 7 summarises the experiment setup involving the ESLs and the WiFi access point, connecting the ESLs via Bluetooth and the consumer's mobile phone via WiFi signals. Depending on the hardware capabilities, the AP either runs an edge version of the product database or is furthermore connected to a server or cloud service that manages the relevant product data. The AP would not need to have a BLE interface. The hypothesis is that with a spatially distributed grid of ESLs, the consumer's distance as well as the angle from the shelf front can be sufficiently determined by the beacon signal strength in order to give navigation advice.

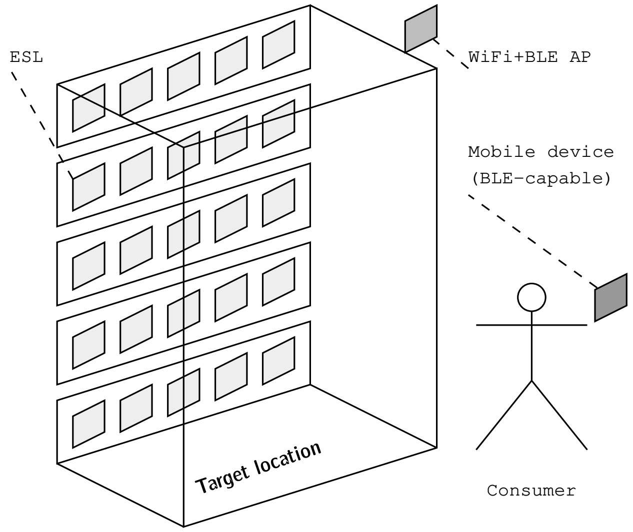


Fig. 7 Distance and angle determination to shelf front array of ESLs

Mathematically, the shelf has a width of 0.8 m and a height of 1.7 m. The two reference positions are 2.5 m in front of the shelf, with a shift of 2 m to the left and to the right of the shelf's centre. Through trilateration, this translates to a detectable shift in distance by approximately $\sqrt{2.5^2 + 2.35^2} - \sqrt{2.5^2 + 1.65^2}$, roughly 43 cm. Measured but not considered further for the analysis is the detectable shift in altitude with small distance variations by roughly 10 cm assuming the mobile device is held at half the shelf height.

4.2 Findings

In an outdoor baseline experiment, in cooperation with a physical store, a Minew BLE 5.0 beacon was placed behind the store's glass front in order to detect its signal strength based on the distance and with the help of GPS as means of verification. Then, due to the signal's heavy deviation, a stack of five beacons was placed just next to the single beacon, and measurements were repeated a few times. Fig. 8 summarises the results. It is clear that the signal stability has improved with the stack, covering more waypoints, but it still varies occasionally. Nevertheless, this baseline confirms that using multiple beacons is helpful, at the expense of redundant hardware investment. Moreover, it confirms that even economic beacons are sufficient to achieve the precision needed in outdoor environments, where deviations of one or two metres are tolerable.

Fig. 8 Signal strength of a beacon in an outdoor scenario: single (left), stack (right)

The subsequent experiment based on the shelf front array of ESLs is considered next. The consumer needs to pass through a corridor and enter an adjacent room that contains the shelf. The signal diffusion is therefore disturbed by walls and other obstacles. No reference positioning as with GPS exists, but the calculated distance should consistently shrink on the consumer's path towards the shelf and, implicitly, towards the desired product on the shelf. In line with this argumentation, the angle of a consumer to the shelf front should be determinable by differences in distance between the two sides of the shelf. All measurements were repeated 100 times with one second inter-measurement interval, resulting in about 10 minutes continuous observation. While not practical for real navigation scenarios, this setting shall represent the upper limit on obtainable precision.

The results of a static set of measurements from both a left angle and a symmetric right angle, each located about two meters from the shelf, is shown in Fig. 9. All signals strengths from the 100 rounds are aggregated through a mean average function. More sophisticated techniques such as outlier detection and voting (over independent observers) would be possible but are omitted from this exemplary experiment. Still, the ESL grid does not give any information from which distance or angle could be inferred reliably. Evidently, several signals deviate stronger than others. This behaviour confirms the baseline observation. The differences in deviation and signal attenuation could be learned during one or more calibration rounds to influence the interpretation of raw measurements by translating them into device-independent and situation-independent values.

Three characteristic signal strengths (Received Signal Strength Indication, RSSI) of BLE transmitters are shown for reference in Fig. 10. Apart from being device-specific and placement-specific, including any obstacles to the line of sight (LOS), their behaviour over time depends on the battery charge level among other factors. Given the lifetime of several months, the influence of this factor can be dismissed, and the RSSI spectrum can be reduced to a

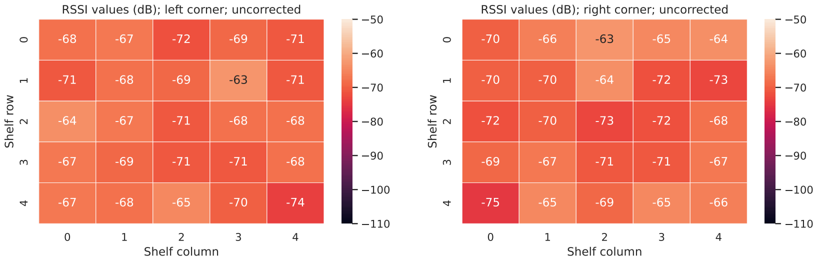


Fig. 9 Signal strength of a grid of beacons/ESLs on a shelf

simplified mean value given a non-disturbed LOS which, while not being realistic in physical scenarios, should be sufficiently valid to find a first solution approach in a lab environment.

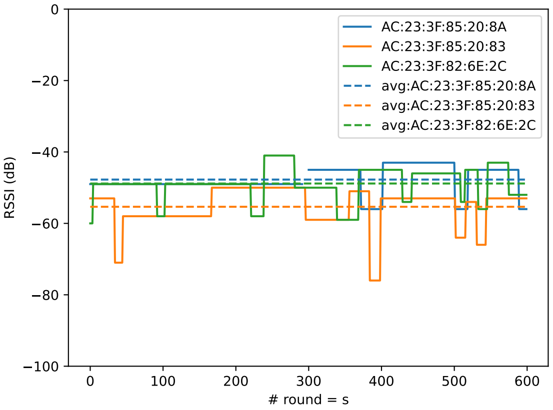
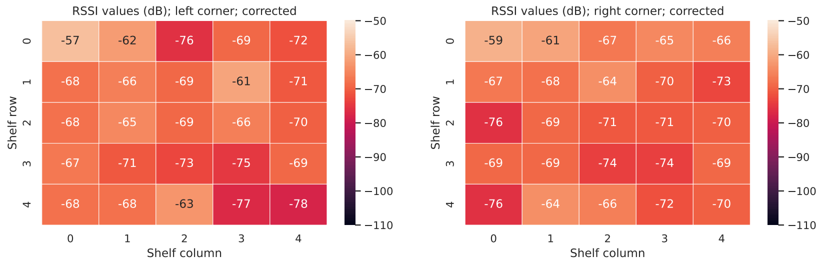


Fig. 10 Calibration function to achieve characteristic RSSI profile per device

Consequently, each measured RSSI of a device i in a fixed set of devices $rssi$ subject to prior calibration can be adjusted by this mean value as explained in Eq. 1. Due to signal propagation behaviour, the calibration needs to be performed at varying distances; in this experiment, at 1.50 m for roughly matching the shelf front layout.

$$rssi\_adj_i = rssi_i + avg(rssi_i) - avg(rssi) \tag{1}$$

With the corrections applied, the adjusted RSSI values appear differently as shown in Fig. 11. Interpreting these matrices is unnecessarily hard for humans, and due to the problem setting can be simplified by a columnar projection, referring to the reduction of 3D navigation to 2D navigation, the usual task when holding a mobile device at the same altitude. In this projection, all measurements across a column are aggregated, here specifically through a mean average although again more sophisticated aggregations including outlier filtering could be possible.



RSSI values (dB); left corner; corrected

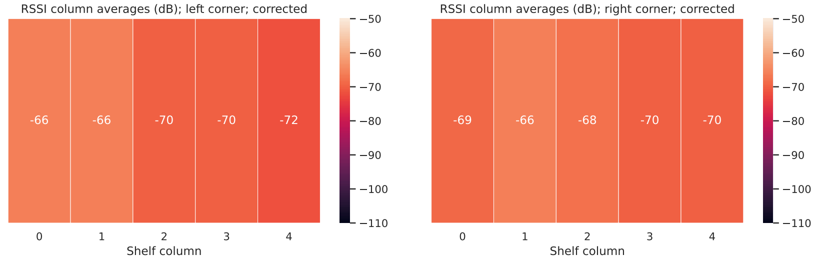
Shelf row	0	1	2	3	4
0	-57	-62	-76	-69	-72
1	-68	-66	-69	-61	-71
2	-68	-65	-69	-66	-70
3	-67	-71	-73	-75	-69
4	-68	-68	-63	-77	-78

RSSI values (dB); right corner; corrected

Shelf row	0	1	2	3	4
0	-59	-61	-67	-65	-66
1	-67	-68	-64	-70	-73
2	-76	-69	-71	-71	-70
3	-69	-69	-74	-74	-69
4	-76	-64	-66	-72	-70

Fig. 11 Signal strength of a grid of beacons/ESLs with correction applied

The result of the columnar projection is shown in Fig. 12. For the left corner, the results are satisfying and show a monotonic RSSI difference of approximately 6 dB for the distance difference of 80 cm. For the right corner, the results are not satisfying due to a bimodal minimum RSSI distribution. This implies that although the shelf front array technique is promising, it requires further research work to better understand the underlying cause of the result data differences. Apart from using better quality hardware, calibration using the txPower signal flag would be a possible solution that can be attempted within the same shelf lab environment.



Shelf column	0	1	2	3	4
RSSI column averages (dB); left corner; corrected	-66	-66	-70	-70	-72
RSSI column averages (dB); right corner; corrected	-69	-66	-68	-70	-70

Fig. 12 Columnar signal strength after applying corrections

5 Conclusion and Outlook

This chapter has given a broad overview about the topic of smart shopping and its conceptual evolution along with research in software, hardware, networking and signalling. It has specifically introduced a taxonomy of smart shopping location support enabled by mobile devices and pervasively deployed things, a lab environment centered around a smart shopping shelf, and an exemplary experiment related to real-time location services and navigation.

Much larger economic transitions involving circular economies, autonomous cargo networks and omni-channel distribution are ahead of developed societies. Smart shopping can ensure on an individual level that consumer preferences are taken into account in this evolving macroeconomic landscape, and could be further combined with gamification and social links for instance to foster more regional product circulation. The research needs in smart shopping have been outlined and underlined with an indoor navigation experiment relative to a set of already deployed ESLs which showed promising results that can however not yet be directly transferred to practical applications due to deficiencies in the underlying hardware. New technology such as BLE 5.1+, as well as combined devices (beacon, sensor, display), are being deployed in stores and will gradually mitigate these limitations, along with more 5G and LoRaWAN coverage of outdoor areas which in Switzerland already reaches 98% and 97%, respectively. With a physical lab environment and software research prototypes available, innovative science-based solutions for smart shopping can be transferred to smarter cities and regions in the future.

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