Introduction

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Chapter 1
Introduction

Every person needs to eat regardless of whether he/she follows a “live to eat” or a “eat to live” philosophy. As food intake is an inevitable aspect of survival, food and everything around food have continuously evolved from time immemorial. One of the major aspects that has been experiencing much technological innovation is cooking, and in a broader sense, the kitchen. With lives of people becoming busier every day, the kitchen will certainly be the focal point of innovation in the near future.

With the emergence of the Internet of Things (IoT) technologies, the concept of ‘Smart Kitchen’ or ‘Connected Kitchen’ [1] is being developed. This concept has brought a wave of smart and connected devices that has transformed the way we cook and interact with our kitchen appliances. It facilitates many interesting and important applications that cater to the busy lifestyles of today, such as enabling the appliances to be controlled from smartphones, and cooking by uploading recipes from a remote location which saves time as compared to the conventional cooking methods.

An imminent technological development in the smart kitchen domain is the concept of ‘Cordless Kitchen’ [2]. This concept, introduced by the Wireless Power Consortium (WPC) [3], does not require the appliances to have power cords or batteries to operate. Instead, they are powered by inductive power sources (or power transmitters) that may be built into a kitchen counter, cooktop (hob), or a table. The appliance needs to be simply placed on top of the power transmitters and the user should be able to cook, interact and control the appliance remotely.

The Cordless Kitchen standard, also known as ‘Ki’, is based on the principles of ‘Qi’ wireless charging technology which is already prevalent in the market for charging smartphones. Ki, however, is designed for powering higher input wattage equipment. There are about 580 consortium members (as of March 2020) in WPC with many renowned Original Equipment Manufacturers (OEMs) such as Philips, Samsung and Robert Bosch. Some manufacturers are also extending this to charge laptops (e.g. Powermat Technologies).

As Ki does not deal with networking the appliances, this book focuses on getting these cordless kitchen appliances connected to the Internet with minimal changes on

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the appliances (or devices) and networking stacks. In this chapter, we shall introduce the concept of cordless kitchens and technologies involved, and then give an overview of why connecting the appliances to the Internet is non-trivial.

The reader can learn about the ‘Ki’ cordless kitchen operation in detail in Chap. 2. We shall walk the reader through the complete design process: Chap. 3 shall discuss possible architectures to connect the appliances to the Internet; Chap. 4 shall describe the state of the art and present why this problem needs novel solutions; Chap. 5 details the challenges for providing Internet connectivity and describes how the TCP/IP protocol should be adapted to the cordless kitchen system. A thorough evaluation of the proposed solutions is presented in Chap. 6, along with few implementation recommendations. Other factors affecting the performance that a solution architect must consider are explained in Chap. 7.

1.1 Overview of the Cordless Kitchen Concept

The main goal of the cordless kitchen concept is to eliminate power cords in kitchen appliances. Connecting the appliances to the Internet would bring in ease of use. For example, users can upload recipes, monitor the dish and appliance and begin cooking when still on the way home. These goals together will provide the user with a truly wireless, smart-cooking experience.

1.1.1 Benefits of Cordless Kitchen

Ki is designed for cordless kitchen appliances that can be powered with a maximum of 2.2 kW. For heavy appliances, such as a refrigerator, that are stationary, the concept of a cordless kitchen is neither required nor efficient. Some of the benefits of the cordless kitchen are listed below.

- **Space efficient:**
  - Better usage of limited kitchen counter spaces and tables as the same space can cater to food preparation, cooking and cleaning.
  - Cordless appliances are easy to store.
- **Smart:**
  - Two-way communication between the appliance and the power transmitter allows for intelligent features such as consistent and power-efficient cooking, as the amount of power transferred is equal to what the appliance expects.
  - Adding Internet connectivity in the cordless kitchen would enable remote cooking, where users can control the appliances remotely, upload recipes and software updates, enable IoT communications, etc.

  - Cookware can be made smart (e.g. smart pans).
- **Safe and Robust:**
  - Inductive power transfer is robust against water and dirt, as they have no effect on the operation or safety.
  - There is no electrical shock hazard.
  - The bottom of the appliances remains cool.
  - Foreign object detection functionality avoids accidental heating of foreign objects like spoons, knives, etc.
  - Leaving the power cord plugged in presents a safety hazard to some appliances. This can be solved by using the smart cordless kitchen.
  - If the appliance is knocked over or moved off the transmitter location, it immediately stops receiving power.
- **Interoperability:**
  - One standard power transmitter can be used for all types of cordless appliances.
- **Convenient and Clean:**
  - Reduces clutter in the kitchen.
  - As the power transmitters are installed underneath kitchen counters and tables, all the wiring is hidden from the view. This enables a sleek, ultra-modern design for the kitchen.
  - Kitchen countertop and the appliances are easy to clean.
- **Appliances can be moved:**
  - Enables table-top cooking.
  - Heat/cook where needed, efficiently. For example, appliances can be moved from the countertop to the dining table for keeping warm.

1.1.2 Use-Cases

Any kitchen appliance can be made cordless. A few examples include toasters, coffee makers, rice and slow cookers, deep fryers, etc. Three main use-cases are proposed by WPC [4].

Hybrid cooktops: In addition to the traditional hobs on an induction cooktop, one or two hobs will be Ki-compliant power transmitters. This enables versatile cooking along with traditional cookware when cooking multiple dishes. This is completely safe as the Ki-compliant cookware have their own integrated controls to prevent any undesired heating while the traditional cookware cannot draw any power from the power transmitter.

Kitchen counters: Installing a power transmitter under a kitchen counter enables a cordless kitchen. A variety of appliances can be placed on it allowing one to cook an entire meal on the countertop.

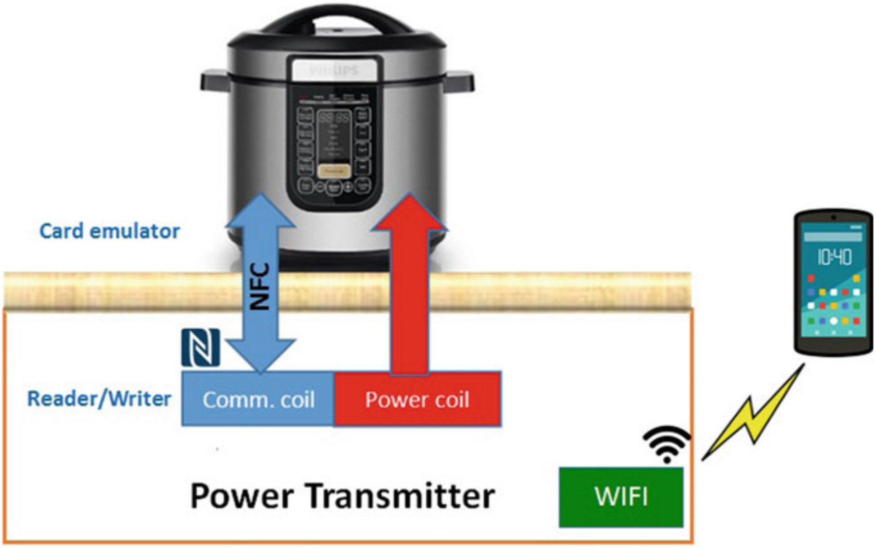

Fig. 1.1 The cordless kitchen concept

Dining tables: Making a dining table Ki-compliant allows for keeping the food hot and also cooking without any safety hazards (e.g. Chinese hotpots and cheese fondue) even with small children around.

1.1.3 System Architecture

In order to eliminate power cords, the appliance will be powered by inductive power transfer in which a permanently mounted Power Transmitter (PTx) or a Magnetic Power Source (MPS)[1] as shown in Fig. 1.1. The PTx contains a coil that draws power from the mains and transfers it via electromagnetic induction to another coil placed in the appliance [5]. The power is then converted back into electrical energy and/or heat for cooking within the appliance.

Interoperability: A Wireless Power Consortium (WPC) cordless kitchen-compliant appliance and power transmitter support interoperability, where one standard power transmitter can be used for all types of appliances. It is safe and robust as there will be no electrical shock hazard with inductive power transfer.

Safety: The Foreign Object Detection (FOD) functionality avoids accidental heating of foreign objects like spoons, knives, etc.

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[1] PTx and MPS both represent the inductive power source and the terms are used interchangeably in the book.

Unlike traditional kitchen appliances, cordless kitchen appliances are made intelligent. They communicate with the PTx to ensure that the amount of power received remains within the limits of the appliance and according to the input from the user. The communication between the cordless appliance and the PTx takes place using a Near-Field Communication (NFC) [6] channel, as shown in Fig. 1.1. This makes cooking much more precise, responsive and repeatable with cordless appliances. The next section gives an overview of the NFC communication interface.

1.1.4 How Does it Work?

When an appliance is placed on the PTx, the PTx ‘talks’ to the appliance over the NFC channel in order to negotiate the amount of power to transfer. Here, the PTx operates in the NFC Reader/Writer (RW) mode and the appliance operates in the NFC Card Emulator (CE) mode, as depicted in Fig. 1.1. The communication is initiated and controlled by the PTx, i.e. it behaves as the master and the appliance as the slave. However, when it comes to power transfer, the appliance controls the amount of power it receives from the PTx by sending frequent power control messages.

The NFC technology, like the inductive power transfer, is also based on the concept of electromagnetic induction which enables short-range communication between two compatible devices. NFC operates with low magnetic field strength, and the presence of a high magnetic field corrupts the communication carrier of NFC. In the case of a cordless kitchen, both wireless power transfer and NFC communication need to work together in the same system. As the inductive power source generates a very high magnetic field that can disrupt the NFC communication, WPC has proposed a solution where the wireless power transfer and the NFC communication operate in a time-multiplexed fashion as shown in Fig. 1.2. Here, u_{op} represents the operating voltage and f_{op} represents the operating frequency. The NFC communication takes place at zero crossings of the power signal, for a duration of $T_{zero} = 1.5$ ms. For example, when a power signal with an operating frequency (f_{op}) of 50 Hz is used,

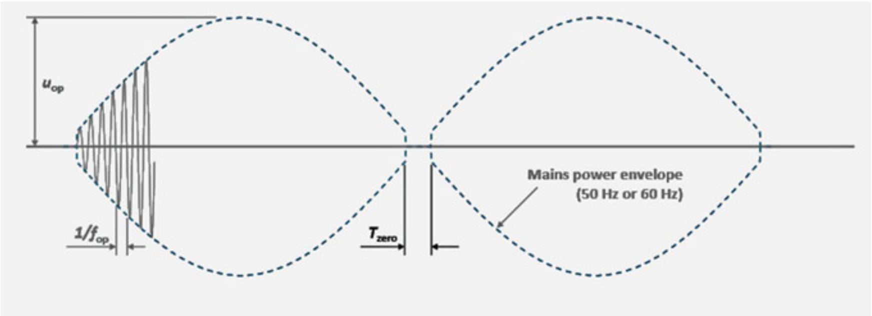


Fig. 1.2 Time-multiplexing of the power and the communication signals

Fig. 1.3 NFC antenna and primary coil in the PTx

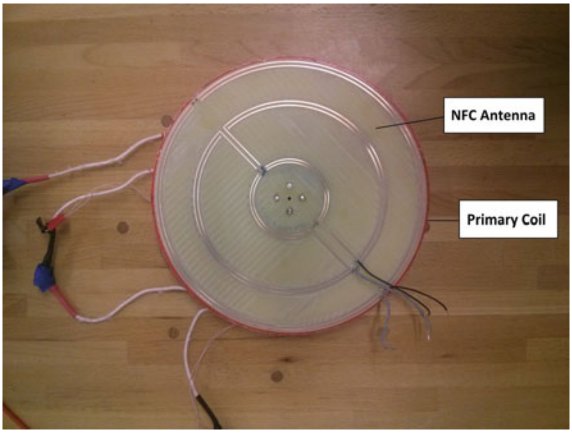
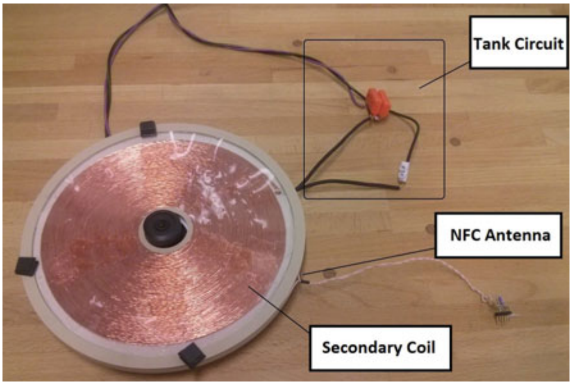


Fig. 1.4 NFC antenna and secondary coil in the appliance



the power transfer would take place for 8.5 ms and the communication for 1.5 ms. This would repeat every 10 ms or in every half cycle of the power signal. It takes less than 1 µs to stop the power signal near the zero crossings and start the NFC communication. This avoids interference from the magnetic fields of the power signal during the 1.5 ms of NFC communication.

The communication complies with the ISO/IEC 14443 standard defined for near-field communications. The NFC antennas in the cordless kitchen specification are significantly larger than the ones specified in the standard. They are circular in shape and the coils used for inductive power transfer are concentric with each other, as shown in Figs. 1.3 and 1.4. The cordless kitchen specification supports NFC bit rates of 106, 212, 424 and 848 kbps. However, with the time-slotted mode, these bit rates reduce to lower values.

New NFC read and write commands are defined in the cordless kitchen specification to reduce the communication overhead and meet the 1.5 ms time slot requirement. The commands follow the ISO/IEC 14443 half-duplex transmission protocol. Table 1.1 shows the number of bytes that can be read using different NFC bit rates

Table 1.1 Number of bytes that can be sent using the new NFC read command at different data rates

Bit rate (kbps)	N° of bytes in payload
106	5
212	19
424	48
848	104

Table 1.2 Number of bytes that can be sent using the new NFC write command at different data rates

Bit rate (kbps)	N° of bytes in payload
106	4
212	18
424	47
848	103

in the time-slotted mode. The new write command supports similar payload sizes as shown in Table 1.2. These commands carry messages containing measurement data, operating limits, control data and auxiliary data for Internet connectivity. Further details about the NFC protocol extensions are provided in Chap. 2.

1.1.5 Internet Connectivity in the Cordless Kitchen

One of the requirements of the cordless kitchen is to enable Internet connectivity for users to control the appliances remotely, upload recipes and software updates, etc. Typically, the appliances need not support connectivity when they are away from the PTx. A straightforward way of providing Internet connectivity to the kitchen appliances would be to install Wi-Fi modules in them. However, in a cordless kitchen system, the appliance will not always be powered. Furthermore, when the PTx goes into standby mode, the appliance will not receive any power, i.e. it will be switched off. Therefore, the Wi-Fi module in the appliance will not be awake at all times to provide Internet connectivity, and would be available only when the appliance is placed on top of the PTx. This would lead to the loss of messages. Therefore, having a Wi-Fi module in every single kitchen appliance would be inefficient and unnecessary.

This research focuses on providing efficient Internet connectivity and enabling reliable communication with the appliances. We conclude this chapter with the challenges and proposed solutions in the next section.

1.2 Challenges and Solutions

Two main challenges are addressed through this research.

1. **Providing efficient Internet connectivity to the cordless kitchen appliances**
   On contrary to using a Wi-Fi module on each appliance, a Wi-Fi module or an Ethernet connection could be installed in the PTx, and the already existing NFC communication channel could be used to indirectly connect the cordless appliance to the Internet via the PTx. This would also make the appliances cost-effective as there can be only one Wi-Fi/Ethernet connection in the kitchen which could be used by all the appliances. Furthermore, when a message arrives onto the PTx, it can power up the appliance, if placed on the top of the PTx, and establish the communication.
   Two architectures are proposed in this book to provide Internet connectivity in the cordless kitchen through the NFC channel. Both these architectures are suited for the TCP/IP protocol stack. In the first architecture called the Proxy architecture, the appliance only sends the application data to the PTx via the NFC channel, and the PTx takes the responsibility of creating/processing TCP/IP packets and sending them to the end-user device. In the second architecture called the Bridge architecture, the appliance sends complete TCP/IP packets to the PTx, and the PTx only forwards these packets to the end-user device via the Wi-Fi channel. The book mainly focuses on the implementation and performance analysis of the bridge architecture where TCP/IP is tunneled over the time-slotted NFC channel.
2. **Adapting the TCP/IP protocol to a low bandwidth time-multiplexed NFC channel such that low end-to-end latency is maintained in the TCP applications**
   Most applications use TCP as the transport layer protocol in order to provide reliable end-to-end communications, and therefore it will be used in the appliances as well. However, NFC is designed for exchanging small payloads with data rates up to 848 kbps in normal mode and around 83.2 kbps in the time-slotted mode. On the other hand, TCP/IP is designed for exchanging a large amount of data and at much higher data rates to get a considerable performance. Tunneling a heavy-weight protocol like TCP/IP over a constrained channel like the time-slotted NFC would increase the system latency due to the large overhead introduced by the TCP/IP protocol with the TCP handshake/termination sequences, acknowledgment mechanism, header overheads, etc.
   The Internet applications of the cordless kitchen such as remote user control and online cooking are firm and soft real time as they require fast response time. Missing deadlines in these applications may not be hazardous, but it would definitely affect the cooking procedure and the quality of the food. Motivated by this demand, the research aims at adapting the TCP/IP protocol to the time-slotted NFC channel such that the TCP applications have low end-to-end latency.
   In this work, the feasibility of using the bridge architecture for firm and soft real-time applications is analyzed by studying performance bottlenecks and highlighting various factors affecting the latency, throughput and bandwidth utilization of

the NFC channel. Since the channel has unique properties, the challenges posed need to be solved. Several solutions and adaptation of TCP are proposed for the bridge architecture, as illustrated below.

a. Due to the delay on the NFC channel, TCP will experience spurious retransmissions.

To eliminate these, a generalized solution is provided using which appropriate TCP Retransmission Timeout (RTO) values can be calculated depending on the packet size and the data rate of the NFC channel being used.

b. Although TCP is designed to adapt the RTO over time by estimating the delay on the channel, it does not consider the payload sizes in this estimation. This leads to choosing an incorrect RTO value for this NFC channel. Therefore, if the payload size varies, TCP still experiences spurious retransmissions.

This research also proposes a new algorithm for dynamic RTO estimation for the TCP/IP packets considering the channel delays. This algorithm ensures that optimum RTO values are set for each packet such that spurious retransmissions are eliminated, and delayed retransmissions are prevented in case of packet loss.

c. The bridge architecture suffers from packet drops at the NFC interface due to the processing speed mismatch between the TCP/IP stack and the NFC module.

An NFC channel sensing mechanism is defined so that the TCP stack is slowed down to match the transmission speed of the NFC channel, thereby achieving an optimum inter-packet delay.

d. The other parameters of TCP, such as contention window size and maximum segment size, have an influence, which need to be studied. Also, the influence of bit errors in the NFC channel needs to be studied.

The book also throws some light on the parametric analysis of other factors that affect the system performance such as NFC bit error rates, communication time-slot sizes, presence of non-TCP/IP messages on the NFC channel, etc.

Using the new RTO estimation algorithm and the NFC channel sensing mechanism, a reduction of about 38% in the system latency is achieved at an NFC data rate of 11.2 kbps, and up to 53% at 24 kbps in the time-slotted mode. The methods to achieve this will unfold in the next chapters of this book.

1.3 Takeaways

The important takeaway message from this book is how to enable Internet connectivity to the cordless kitchen appliances despite the slow and time-slotted NFC channel. The minimal changes needed to the Internet stack are presented. Another takeaway message for the implementers/device manufacturers is what to expect when the networking parameters are tuned.

For the WPC consortium members and the standards working group, several possible architectures to connect appliances to the Internet are presented with pros and cons. We argue that a method to connect to the Internet should be included in the standards for better interoperability between the power transmitters and the appliances.

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