Wireless Connectivity
Wireless Connectivity

An Intuitive and Fundamental Guide

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In memory of my father, the unshakeable optimist.
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Foreword

First: But, Why?
Why should one dare to write a relatively long book in a digital age, where everything seems to be quickly found online and watching video tutorials is used as a substitute for reading? Why read, let alone write, a long text when a single tweet results in thousands of workers getting laid off or somebody becoming a millionaire in a day? And, last, but not least, why put in so much effort, knowing that, eventually, despite all the measures, the PDF of the book will be available for illegal download at a phony website?

A book or a textbook still has its role in the digital age, but this role is significantly different from the times when books were the ultimate source of information and knowledge. It should rather be understood as a gateway to knowledge, a gadget that helps to make sense of the massive amount of online data, a hitchhiker’s guide for receiving, filtering, and learning from the overwhelming waves of information. As for the illegal copies: if you are reading this on an illegal copy, then it is fair to tell you that it is getting really boring from now on, so you can stop reading.:

Wireless became Huge and Complex
This role of a “gateway to knowledge” was one of the motivations behind writing this book. The area of wireless communications has developed immensely over the last three decades, generating a large number of concepts, ideas, articles, patents, and even myths. Identifying the crucial ideas and their interconnection becomes increasingly difficult. The area of wireless connectivity grew to be very complex, to the level where the specialists working in one part of the system, say hardware, did not know much about the functioning of the high layer protocols, and vice versa. In the extreme case, this ignorance about the concepts and functioning of the other parts of the communication system led to the “only-my-part-of-the-system-matters” attitude, sometimes resulting in disastrously sub-optimal designs.

In order to see how much wireless communication has developed in volume and complexity, here is an ultra-short overview of the generations of wireless mobile communication systems. It started with the “modest” ambition of 2G being reachable for a phone call wherever you are moving, but the unlikely hero was the short message service (SMS) that brought texting as a new social phenomenon. It was perhaps this unlikely hero that planted the obsession with the “killer application” during the development of 3G. The advent of the smartphone has shown that there was not a single killer application,
but a gateway to the internet, a gadget with many apps, a hitchhiker’s guide to multiple applications [sic]. Only with the data speeds offered by 4G did the smartphone start to reach its full potential, completely transforming work and play. At the time of writing, we are at the dawn of the deployment of 5G, still with a lot of predictions, enthusiasm, and skepticism. The working version of the 5G ambition is to offer truly ubiquitous and reliable coverage to the humans, but also wirelessly connect machines and physical objects.

Note that this ultra-short overview is unfair to a lot of other wireless technologies that are omnipresent and play a crucial role in daily life, such as Wi-Fi and Bluetooth. The tone in the book is leaning towards mobile wireless cellular networks, but the overall discussion is kept generic, not tied to a particular wireless system or technology.

How this Book is Structured
The book does not follow the established, linear structure in which one starts from the propagation and channels and then climbs up the protocol layers. Here the approach has been somewhat nonlinear in an attempt to follow the intuition used when one creates a new technology to solve a certain problem. With this approach, we state a problem from the real world and create a model that reflects the features of the problem. The model is a simplification, a caricature of the reality, but as every good caricature, it captures the essential features. A certain model (for example, a collision model of a wireless channel), allows the system designer to propose solutions that reside within a subspace of the space of all possible solutions to the real communication problem. By enriching the model (for example, adding a capture and interference cancellation to the collision model), the system designer can devise solutions that go beyond the boundaries of the previously mentioned subspace. Practically each new chapter brings enrichment of the models, presenting system/algorithm designs that extend the ones developed for the simpler system models.

Each chapter starts with a cartoon that carries the main message of the chapter. The narrative in the book uses characters as it facilitates the discussion about communication between different parties. This is inspired by the security literature, which deals with Alice, Bob, etc. Here I have started from the other side of the alphabet, which is populated by the letters commonly used in communication theory. The characters are Zoya, Yoshi, Xia, Walt, Victoria (which happens to be the name of my mom) and Umer, and, yes, they are more international compared to Alice and Bob. The base stations are named Basil and Bastian for obvious reasons.

Among the references in “further reading”, I have inserted references to some of the research works co-authored by me. This is not to boost my citations by a self-citation (which is, righteously, often not counted in the academic record), but rather to offer a reference that shows that I, the author, have made an actual research contribution to the area. This can only increase the credibility of what is written in the chapter.

Objectives and Target Audience
When I started the book, the objective was to make it suitable for casual reading and use almost no equations. In the meantime, the number of equations increased, but still far below the number in standard textbooks on wireless communications, such that there is still hope that the reader can read it casually. Yet, the fact that there are five problems after
each chapter indicates that the book can also be used as a textbook. However, for in depth reading, the reader should rely on the literature in “further reading”.

The target audience is:

- Students in electronics, communication and networking. Some of the problems at the end of the chapters are actually mini-projects, which the students can do over an extended time. This is suitable for both graduate and undergraduate courses. Clearly, if used as a graduate course, then there is more reliance on external literature.

- Wireless engineers that are specialists in one area who want to know how the whole system works, without going through all the detail and math.

- Computer scientists that want to understand the fundamentals of wireless connectivity, the requirements. and, most importantly, the limitations.

- As wireless connectivity starts to play a big role in a large number of cyber-physical systems, such as smart grids, transport, logistics or similar, the engineers specializing in those areas can obtain an insight into some of the essential wireless concepts.

- As a supplement to other books on wireless connectivity that deal with the detail of analysis and design of specific technologies.
Acknowledgments

Even when a book has a single author, a large part of the authorship goes to the colleagues, friends, and family that provided inspiration, criticism, a gentle push when things looked impossible and a reminder that Sisyphus was only a mythical creature.

I am deeply grateful to Osvaldo Simeone (King’s College London) for enormous support during the preparation of this book. The credit for the idea of using cartoons should go to him. He could absolutely always find the time to read the chapters that I was asking him to check, and provide prompt and rich feedback. I have been fortunate to have him, an exemplary erudite researcher, as a collaborator over many years.

Three people stood out in encouraging me throughout the long writing of the book. Jørgen Bach Andersen (Aalborg University), Angel Lozano (Pompeu Fabra University) and Hiroyuki Yomo (Kansai University). Jørgen provided me with very valuable feedback on Chapter 10 (Space in Wireless Communications). Angel removed my doubts about the usefulness of Chapter 9 (Time and Frequency in Wireless Communications). Hiroyuki decided to use this as a textbook in the early stages, when I presented him with the book concept.

I am very thankful for the feedback I got on specific chapters. Two members of my research group provided me with feedback in the early stage of writing and removed some of the doubts I had about the style. Čedomir Stefanović (Aalborg University) read the first chapters and Nuno Pratas (now with Nokia) read Chapter 6 (A Mathematical View on a Communication Channel). Anna Scaglione (Arizona State University), Emil Björnson (Linköping University) and Elisabeth de Carvalho (Aalborg University) were very kind to read Chapter 11 (Using Two, More, or a Massive Number of Antennas) and provide me with prompt and useful feedback.

A big thank you goes to the members of my research group, who had to be patient with my rants about the book throughout all these years. After one of my lectures for the master students, Rocco Di Taranto (now with Ericsson), at that time my PhD student, asked me: “Where can I read these topics explained in a way in which you did it at the lecture?”. The book idea had been cooking in the background for some time, but this was perhaps the decisive push to write it. Marko Angjelichinoski (now with Duke University) was convinced that the style and the whole book project were very original and I needed to hurry up. I would like to thank Kasper Fløe Trillingsgaard (now with InCommodities) for many stimulating discussion on the information-theoretic aspects. Alexandru-Sabin Bana (Aalborg University) and Radoslaw Kotaba (Aalborg University) helped to prepare a course based on this book and spotted several errors and inconsistencies. While this book was in the final
stages, I was teaching a course at Aalborg University and several students were kind to correct errors in the chapters: Andreas Engelsen Fink, Jonas Ingerslev Christensen, Taus Mortensen Raunholt, Jeppe Thiellesen and Simon Kallehauge.

The cartoons, the cover page, as well as the clipart used to make the figures, were made by Peter Gregson Studio from Novi Sad, Serbia. This is a team of immensely creative people, Jovan Trkulja, Velimir Andrejević and Milan Letić, whose ideas play a significant role in the final look of the book. I would also like to thank Aleksandar Sotirovski for making the first version of the cartoons for some of the chapters, but due to objective reasons could not continue. Thanks to Kashif Mahmood (Telenor) for suggesting Umer as a Pakistani name starting with “U”. I would also like to thank the team at Wiley for being patient and supportive throughout the years, but especially in the final stage: Sandra Grayson, Louis Manoharan, Adalfin Jayasingh, and Tessa Edmonds.

My biggest support through these years came from my family: my wife Iskra, my children Andrej and Erina, as well as our extended family. Family was always there to take the blame when I was performing poorly on time management and planning of the writing. In its most severe form, that blame was ending with a threat that I was going to write something similar to the dedication written by a mathematician, who dedicates his book to his wife and children “without whom this book would have been completed two years earlier”. I am obviously not doing it and, instead, I want to thank them for absolutely always being there for me. I am hoping that some of them will read the book and get to know what I am actually working with. Unfortunately, my father passed away before this book was finished. I am dedicating this book to him.

P. P.
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>AF</td>
<td>Amplify and forward</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic retransmission request</td>
</tr>
<tr>
<td>ASK</td>
<td>Amplitude shift keying</td>
</tr>
<tr>
<td>AMC</td>
<td>Adaptive modulation and coding</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive white Gaussian noise</td>
</tr>
<tr>
<td>BBU</td>
<td>Baseband processing unit</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary phase shift keying</td>
</tr>
<tr>
<td>BS</td>
<td>Base station</td>
</tr>
<tr>
<td>BSC</td>
<td>Binary symmetric channel</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code division multiple access</td>
</tr>
<tr>
<td>CoMP</td>
<td>Coordinated multipoint</td>
</tr>
<tr>
<td>C-RAN</td>
<td>Cloud radio access network</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic redundancy check</td>
</tr>
<tr>
<td>CRDSA</td>
<td>Contention resolution diversity slotted ALOHA</td>
</tr>
<tr>
<td>CSI</td>
<td>Channel state information</td>
</tr>
<tr>
<td>CSIT</td>
<td>Channel state information at the transmitter</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier sensing multiple access</td>
</tr>
<tr>
<td>D2D</td>
<td>Device to device</td>
</tr>
<tr>
<td>DBPSK</td>
<td>Differential binary phase shift keying</td>
</tr>
<tr>
<td>DoF</td>
<td>Degree of freedom</td>
</tr>
<tr>
<td>EGC</td>
<td>Equal gain combining</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency division duplex</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency division multiple access</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward error correction</td>
</tr>
<tr>
<td>GF</td>
<td>Galois field</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>HARQ</td>
<td>Hybrid automatic retransmission request</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>ISI</td>
<td>Intersymbol interference</td>
</tr>
<tr>
<td>LBT</td>
<td>Listen before talk</td>
</tr>
<tr>
<td>LDPC</td>
<td>Low-density parity check</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth orbit</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>LLN</td>
<td>Law of large numbers</td>
</tr>
<tr>
<td>LoS</td>
<td>Line of sight</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium access control; also multiple access channel</td>
</tr>
<tr>
<td>MEC</td>
<td>Mobile edge computing</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple input multiple output</td>
</tr>
<tr>
<td>MISO</td>
<td>Multiple input single output</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum mean squared error</td>
</tr>
<tr>
<td>mmWave</td>
<td>Millimeter wave</td>
</tr>
<tr>
<td>MPR</td>
<td>Multi-packet reception</td>
</tr>
<tr>
<td>MRC</td>
<td>Maximum ratio combining</td>
</tr>
<tr>
<td>NACK</td>
<td>Negative acknowledgement</td>
</tr>
<tr>
<td>NOMA</td>
<td>Non-orthogonal multiple access</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal frequency division multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal frequency division multiple access</td>
</tr>
<tr>
<td>PAM</td>
<td>Pulse amplitude modulation</td>
</tr>
<tr>
<td>PAPR</td>
<td>Peak-to-average power ratio</td>
</tr>
<tr>
<td>pdf</td>
<td>probability density function</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical layer</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase shift keying</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature amplitude modulation</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quaternary phase shift keying</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio network controller</td>
</tr>
<tr>
<td>RRH</td>
<td>Remote radio head</td>
</tr>
<tr>
<td>SC</td>
<td>Selection combining</td>
</tr>
<tr>
<td>SDMA</td>
<td>Space division multiple access</td>
</tr>
<tr>
<td>SIC</td>
<td>Successive interference cancellation</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single input multiple output</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-interference-and-noise ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>TDD</td>
<td>Time division duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time division multiple access</td>
</tr>
<tr>
<td>UEP</td>
<td>Unequal error protection</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra wideband</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero forcing</td>
</tr>
</tbody>
</table>
When the teacher Walt speaks to the students, the shared wireless channel is a blessing.

This is because it is sufficient that Walt says his thing only once, instead of repeating it for each student separately.

However, the shared wireless channel turns into a curse when all others try to speak to Walt at the same time.
1

An Easy Introduction to the Shared Wireless Medium

We start by describing wireless communication through an analogy with a conversation within a group of people, named Zoya, Yoshi, and Xia. We will refer to these and some other characters throughout the book; the characters will stand for wireless devices, base stations, or similar. The data that they want to communicate to each other is the content of their speech, which is part of the conversation. Regardless of the speech content, the conversation can only take place if the participants follow some conversation protocol, such that at a given time only one person speaks while the others listen. How do they agree who gets to speak and who gets to listen? One way would be, before starting the actual conversation, to have them agree upon which conversation protocol should be followed. In that case the information exchanged in that preliminary conversation cannot be regarded as useful data, but rather as metadata, also called protocol information or control information. The metadata is necessary in order to enable the conversation to take place. But then, how do they agree on the protocol for exchanging the metadata?

These questions can go on to infinity, but in a normal situation the communication protocol is agreed upon by either sticking to certain rules of politeness or following visual cues and gestures that facilitate the conversation. In other words, the metadata is exchanged by using a visual communication channel that is different from the speech communication channel. However, in a commonly encountered wireless communication system there is only one communication channel through which both the data and the metadata should be sent. This is not to say that it is not possible to have one wireless communication channel for data and a separate one for metadata; even if such separation exists, then what is the protocol for exchanging the meta-metadata that is used to agree how to send the metadata?

This gets obviously complicated, but the bottom line is that we will always hit the problem of communicating over a single shared wireless channel. Now, taking the fact that there is a single channel for communicating both the data and the metadata, the key point of the analogy with the conversation is to put Zoya, Yoshi, and Xia in a dark room, such that they have only speech as a means of communicating (we exclude tactile communication) and no visual cues can be of help. In that setting, the audio channel should be used both to coordinate the conversation and to carry the actual content of the conversation.

This is the common situation in which wireless communication systems operate and will be the subject of this chapter. Here are some examples of the questions that will be discussed. If Zoya and Yoshi want to talk to each other, how do they agree who talks first and who listens first? If both Xia and Yoshi want to talk to Zoya, how should they agree who
takes a turn to speak at a given time, so that they don’t all talk simultaneously? Solutions to these problems are provided by various protocols for controlling the access to the medium; hence the name MAC (medium access control) protocols, and they are of central importance in wireless communication systems.

1.1 How to Build a Simple Model for Wireless Communication

1.1.1 Which Features We Want from the Model

The main feature of the wireless communication medium is the fact that the medium is shared, in the same way in which the air through which the sound propagates is shared among the people having a conversation. MAC protocols enable multiple wireless communication users and devices to share the medium and send/receive data.

First, we must agree on how the system operates and what it takes to have a signal from one communication node received correctly at another node. In other words, we need to settle on a suitable system model: a set of assumptions that will allow us to talk about communication protocols and principles in a setting that is simple, but sufficient to contain the necessary properties of a shared wireless medium. We build the initial model by relying on a common sense analogy with the spoken conversation, as it captures three fundamental properties of wireless communication: broadcast, interference, and half-duplex operation. We illustrate these features by observing a conversation between Zoya, Yoshi, and Xia:

- **Half–duplex:** A given person, e.g. Zoya, cannot speak and listen at the same time.
- **Broadcast:** If Zoya has information to convey to Yoshi and Xia, then, provided that both Yoshi and Xia are listening, Zoya needs to say her message only once, and not repeat it individually to Yoshi and to Xia.
- **Interference:** If Yoshi and Xia speak simultaneously, Zoya will not understand either of them.

The descriptions above are arguably not always correct, but they do represent what is common sense for a conversation. Furthermore, the analogy of the communication problems with the conversation between Zoya, Yoshi, and Xia is useful, but it has its limitations, which will be pointed out when necessary.

1.1.2 Communication Channel with Collisions

For the purpose of this chapter, we define a communication channel to be the physical resource that is used for a wireless transmission. In that sense, in spoken communication, the channel is created by the audible vibrations that take place in air or even another sound-propagating medium. It is useful to note that the communication channel is not the whole physical medium with all the vibrations, since there are vibrations that cannot be registered by ear and thus do not carry useful audio information. Furthermore, spoken communication uses a single communication channel: one cannot switch to another channel, such as in a TV receiver, in order to listen to the desired speaker and avoid the undesired one.

As already stated above, our discussion will be limited to the case in which all nodes use a single communication channel. In reality that can be, for example, a certain frequency
1.1 How to Build a Simple Model for Wireless Communication

to which all the nodes are “tuned”. Here we use the term “frequency” as it is used in a common language for, say, a TV frequency. One may argue that Zoya and Yoshi can agree to one frequency, while Xia and Walt can agree to tune to another frequency and in this way they do not need to share the channel with the link Zoya–Yoshi. This is indeed possible and we will discuss it in later chapters, when we introduce the notion of separation in frequency. On the other hand, it is also true that Zoya and Yoshi should first use some communication channel to agree upon which frequency they will use for communication. This agreement is, again, metadata or control information, such that the corresponding channel is often denoted as a control channel and can be shared by multiple nodes to come to an agreement about the frequency. For example, if Zoya decides to communicate with Xia, then she knows that she should try to find Xia at the control channel and, upon contacting her, use the control channel to decide which channel/frequency they should both be tuned to in order to communicate the useful data. However, the control channel is a common, shared communication channel and therefore the question of how to share that channel to send metadata remains valid.

The communication model used in this chapter is called a collision model. This is because the central assumption of the model is that if two or more nodes transmit simultaneously, then the interference that they cause to each other is manifested as a collision at the receiver. Upon collision, the receiver does not manage to retrieve any data successfully. Another assumption in the model, not really related to the issue of collision, is that a node operates in a half-duplex manner and cannot receive while transmitting. Most of the wireless systems that we encounter today are not full-duplex, that is, do not transmit and receive simultaneously at the same frequency channel. However, although technologically more complex, it is also possible to have full-duplex operation. Therefore, throughout the chapter we will occasionally revise the half-duplex assumption and discuss the changes that the full-duplex can bring into the design of a specific protocol or algorithm.

The communication between the wireless nodes is based on data packets. A transmitting node is capable of sending $R$ bits per second (bps) such that a packet of duration $T$ contains $RT$ bits. All packets have the same duration, unless stated otherwise. In the collision model, a packet is treated as the smallest, atomic unit of information, such that either the whole packet is received correctly or it is lost. In other words, it is not possible to receive only some bits of the packet correctly. A packet sent by Zoya to Yoshi is received correctly if:

1. Yoshi is in the communication range of Zoya such that the distance between them is less than $d_m$;
2. No other communication node that is within $d_m$ of Yoshi transmits while Yoshi is receiving the packet from Zoya.

The first condition above indicates that each transmission is omnidirectional. Due to the basic property of reciprocity in electromagnetic/radio propagation (see Section 10.9), each reception in our model is also omnidirectional. From this it follows that Yoshi receives a signal as long it is sent from a distance less than $d_m$, regardless of the actual position. The ingredients of the collision model are illustrated in Figure 1.1. Specifically, Figure 1.1(a) depicts the data rate of an idealized single link as a function of the distance between two communicating nodes. An example communication scenario is depicted in Figure 1.1(b), where two nodes are connected by a line if the distance between them is less
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Figure 1.1  Communication model used in this chapter, referred to as a collision model. (a) Simplified dependence between the data rate and the distance, denoting a communication range \( d \). (b) An example topology with possible wireless links among devices. The distance between two connected devices is at most \( d \). (c) Collision model at work for the topology in (b).

than \( d \), indicating the possibility of having a link between them. Figure 1.1(c) exemplifies a possible time evolution of a process of packet transmission in the framework of the collision model. The packet \( Z_1 \) from Zoya to Yoshi is received correctly, while the packet \( Z_2 \) is not, due to collision with the packet \( X_1 \) sent simultaneously by Xia. Note that, by treating a packet as an atomic unit of information, even a partial overlap of \( Z_2 \) and \( X_1 \) causes packet loss. On the other hand, Walt is outside the range of Zoya, such that he can receive \( X_1 \) without being interfered with by \( Z_2 \).

The assumptions of fixed-length packets and always-destructive collisions are weakening the analogy with a conversation. If we think to relate a packet to a spoken word, then not all words have the same length and missing some letters of a word may still not destroy its comprehensibility. In fact, the collision model is rather pessimistic. In reality, one expects