Delay-Doppler Communications: Principles and Applications

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As the interest of wireless communications researchers is moving from 5G to 6G, wireless system design is reconsidered at all layers. One of the key questions for the physical layer is whether orthogonal frequency-division multiplex (OFDM), which has been used for 4G and 5G systems, should be retained, or should be either replaced or complemented by other modulation methods and waveform designs. Thus, the past years have seen a flurry of research on this topic, breathing new life into a topic that had sometimes been considered "mature." One of the most exciting approaches is delay-Doppler modulation, also known as orthogonal time frequency space (OTFS) modulation. While OFDM uses quadrature amplitude modulation (QAM) in the time-frequency domain (each QAM symbol modulates a particular subcarrier for a particular time interval), OTFS performs QAM on a waveform that is concentrated in the delay-Doppler domain. This approach has many advantages, from greater robustness in fast time-varying channels, to the simpler design of precoders and multiple-input multiple-output (MIMO) detectors. OTFS was originally invented by Hadani and collaborators in the mid-2010s and has since gathered great attention, with some 500 research papers written on the topic. The book *Delay-Doppler Communications: Principles and Applications*, written by three researchers who have made very important contributions, for the first time overviews this field with the systematic and expansive descriptions that an authored book can provide.

The book consists of nine chapters, which can be roughly grouped into (i) background, (ii) fundamental modulation and detection of OTFS, and (iii) advanced aspects. The first chapter provides some information on high-mobility wireless systems, and how they are gaining increased importance for modern deployments such as vehicle-to-everything communications, high-speed rail (something that does not exist in the United States but is of huge importance in most other parts of the world), and unmanned aerial vehicles (UAVs). Chapter 2 discusses time-variant wireless propagation channels and the different ways they can be described mathematically, as well as very clearly explaining connections between the physics of moving objects and the impact on the time variations of the channels. In particular, the spreading function (delay-Doppler impulse response) is discussed, since it is the natural way of describing channels for delay-Doppler modulation. Chapter 3 briefly reviews OFDM and points out its advantages and drawbacks. While OFDM has been shown to be information-theoretically optimum under certain ideal conditions, several practical issues — ranging from high peak-to-average power ratio to sensitivity to carrier frequency offset — pose challenges and motivate exploration of alternative modulation methods.

Chapter 4 then begins the core part of the book, providing the fundamental formulation of OTFS as a modulation in the delay-Doppler domain, and relating this representation via the symplectic Fourier transform to the time-frequency domain. The chapter systematically derives the various steps in the so-called OTFS transform, and establishes the conditions on the waveform and its ambiguity function such that perfect reconstruction is possible in a noise-free, non-distorting channel. A compact representation using matrix notation is also derived, and various types of cyclic prefixes are discussed that, in principle, enable demodulation with one-tap equalization. Another way of interpreting OTFS is in terms of the Zak transform, a time-frequency representation that originated in the solid-state physics community but has since found interest in the signal processing community for time-frequency representation of signals. Chapter 5 discusses in detail how it can be used not only to represent OTFS, but also to design transmit and receive filters that optimize bandwidth and time-extent constraints. Chapter 6 then discusses the fundamental detection methods, ranging from simple one-tap and MMSE equalizers, to more complicated message-passing algorithms, to turbo detection that iterates soft information between equalizer and decoder. The chapter also describes a maximum ratio combining receiver that interprets OTSF as two-dimensional spreading so that a two-dimensional Rake receiver can be applied, achieving similar performance as message passing but with lower complexity.

Chapter 7 then moves to the implementation of channel estimation. This is especially important for OTFS because the placement of the pilots and their embedding in the delay-Doppler domain is nontrivial. The chapter also describes a real-time implementation of a complete OTFS system on a software-defined radio platform. Chapter 8 describes the generalization to a MIMO system (making it a full time-frequency-space system). The generalized formulation of transmit signal representation, detection, equalization, and channel estimation are developed. Finally, Chapter 9 discusses the pros and cons of the different types of OTFS implementations, and an outlook on future research topics such as massive MIMO, and joint communications and sensing. An appendix provides several useful MATLAB programs.

The book is written in a very clear style, and allows somebody not familiar with OTFS to quickly understand the essentials of this exciting new topic. Even active researchers in the field will appreciate the clear and consistent description and the extensive intuitive explanations of the finer points of OTFS. The authors have done an excellent job in focusing on the key formulations and their interpretations, and making the book concise (some 250 pages), while also providing extensive references that enable looking up specialized developments. This valuable book will certainly benefit anyone working in the vibrant area of waveform design for 6G.