On communication-theoretic models for programmable wireless environments enabled by reconfigurable intelligent surfaces

Abstract

With the current deployment of the fifth generation (5G) of communication systems, it is now a critical time to identify enabling technologies for the sixth generation (6G) of communication systems. 6G systems are expected to fulfill more stringent requirements than 5G systems, on transmission capacity, reliability, latency, coverage, energy consumption, and connection density. Existing 5G technologies, such as millimeter-wave communications, massive multi-input multi-output systems, ultra-dense heterogeneous networks, are mainly focused on the system design at the transmitter and receiver sides, and on the deployment of additional network infrastructure with power amplification and digital signal processing capabilities and backhaul availability. The purpose of currently available 5G technologies is mainly to cope with or to capitalize on often-unfavorable wireless propagation environments. In fact, the wireless environment has been conventionally modeled as an exogenous entity that cannot be controlled but can only be adapted to. According to this design paradigm, communication engineers usually design transmitters, receivers, and transmission protocols based on the specific properties of the wireless channels and for achieving desired and target performance.

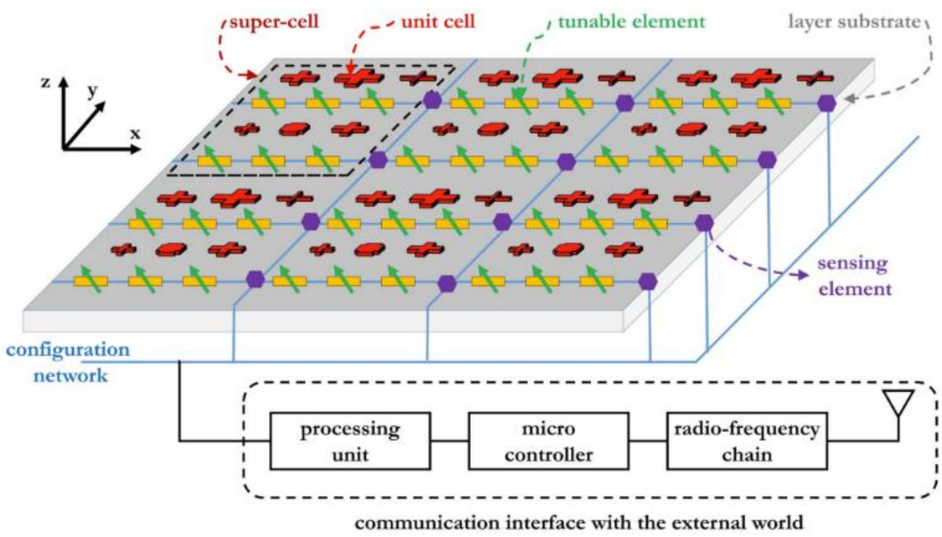

Fig. 1. Conceptual structure of a reconfiguration intelligent surface.

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Recently, **reconfigurable intelligent surfaces (RISs)** have emerged as a promising technology for their capability of customizing the wireless propagation environment through nearly passive signal transformations (see Fig. 1). An RIS is a planar structure that is engineered to have properties that enable the dynamic control of the electromagnetic waves, though, e.g., signal reflections, refractions, focusing, collimation, and their combination. In wireless communications, RISs are intended to realize so-called **programmable and reconfigurable wireless propagation environments**, i.e., wireless environments that are not viewed and treated as random uncontrollable entities but become part of the network design parameters that are subject to optimization for supporting diverse performance metrics and quality of service needs to fulfill the stringent requirements of 6G networks. Recent applications of RISs in wireless communications include their user as nearly passive relay-type surfaces, signal-RF multi-stream multi-antenna transmitters, and reconfigurable ambient backscatters.

Introduction

Increasing data traffic - Wireless connectivity is regarded as a fundamental need for our society. Between 2020 and 2030, it is forecast that the data traffic of the global Internet protocol (IP) will increase by 55% each year, eventually reaching 5,016 exabytes, with data rates scaling up to 1 Tb/s. Besides supporting very high data rates, future wireless networks are expected to offer several other heterogeneous services, which include sensing, localization, low-latency and ultra-reliable communications. 5G networks are, however, not designed to meet these requirements. As the demands and needs become more stringent, in fact, fundamental limitations arise, which are ultimately imposed by the inherent nature of wireless operation.

Current network design assumptions - The first five generations of wireless networks have been designed by adhering to the postulates that the wireless environment between communicating devices (i) is controlled by nature, (ii) cannot be modified, (iii) can be only compensated through the design of sophisticated transmission and reception schemes. After five generations of wireless networks, however, the improvements that can be expected by operating only on the end-points of the wireless environment may not be sufficient to fulfil the challenging requirements of future wireless networks. 6G communication networks is, on the other hand, envisioned to require a new architectural platform that performs joint communication, sensing, localization, and computing, while ensuring ultra-high throughput, ultra-low latency, and ultra-high reliability, which need to be flexibly customized in real-time.

An emerging paradigm: Programming the environment - Major performance gains can be expected by breaking free from the postulate that regards the wireless environment as an uncontrollable element. For example, a typical base station transmits radio waves of the order of magnitude of Watts while a user equipment detects signals of the order of magnitude of µWatts. The rest of the power is, in general, wasted in different ways through the environment by, e.g., generating interference to other network elements or creating security threats, since the propagation of radio waves through the wireless channel cannot be controlled and customized after they are emitted from the transmitters and before they are received by the receivers. An intriguing question was recently brought to the attention of the wireless community: Can this status quo be fundamentally overcome?

The road to smart radio environments - At the time of writing, no precise answer to this question can be given. A plethora of research activities have, however, recently flourished in an attempt of tackling and putting this question in the context of the most promising technologies that were developed during the last decades and that are envisioned to constitute the backbone of 5G networks. The current long-term vision for overcoming the limitations of 5G networks consists of turning the wireless environment into an optimization variable, which, jointly with the transmitters and receivers, can be controlled and programmed rather than just adapted to. This approach is widely referred to as smart radio environment (SRE) or, more recently, intelligent radio environment (IRE), or "Wireless 2.0" in order to emphasize the conceptual and fundamental difference with the designs and optimization criteria adopted in current and past generations of wireless networks. Conceptually, the vision of SREs is depicted in Fig. 2.

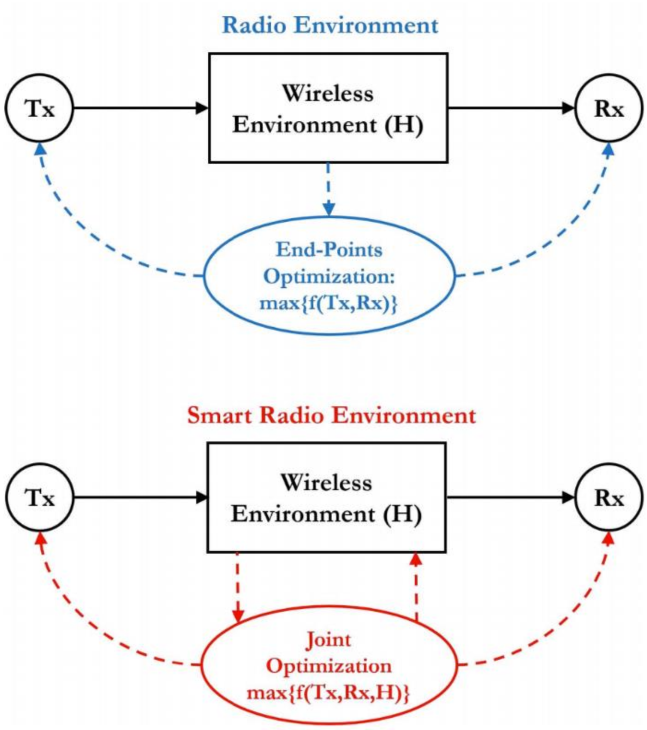

Fig. 2. Radio environments vs. smart radio environments

Communication-theoretic models for programmable wireless environments

Designing wireless networks today: The environment is controlled by nature. Current methods to design wireless networks usually rely on the optimization of the so-called end-points of communication links, e.g., transmitters and receivers. Over the last decades, therefore, many advanced techniques have been proposed for improving the performance of wireless networks, which encompass advanced modulation/encoding schemes and protocols based on using, e.g., multiple antennas at the transmitters, powerful transmission and retransmission protocols, and robust demodulation and decoding methods at the receivers. The wireless environment has, on the other hand, been conventionally modeled as an exogenous entity that cannot be controlled but can only be adapted to. According to this design paradigm, communication engineers usually design the transmitters, the receivers, and the transmission protocols based on the specific properties of the wireless channels and in order to achieve the desired performance. For example, transmitters equipped with multiple radiating elements may be configured differently as a function of the specific characteristics of the wireless channel where they operate, in order to achieve the desired trade-off in terms of spatial multiplexing, spatial diversity, and beamforming gains.

SREs: The environment is generated by nature but is programmable by design - The overarching paradigm that characterizes the design of current wireless networks consists, therefore, of pre-processing the signals at the transmitters and/or post-processing the signals at the receivers, in order to compensate the effect of the wireless channel and/or in order to capitalize on specific features and characteristics of the wireless channel. RISs provide wireless researchers with more opportunities for designing and optimizing wireless networks, which are built upon a different role played by the wireless environment. RISs are, in fact, capable of shaping the radio waves that impinge upon them, after the radio waves are emitted by the transmitters and before they are observed by the receivers, in ways that the wireless environment can be customized, in principle as one desires, in order to fulfill specific system requirements. The wireless environment is, therefore, not treated as a random uncontrollable entity, but as part of the network design parameters that are subject to optimization for supporting diverse performance metrics and quality of service requirements.

Revisiting communication-theoretic models - The concept of SREs introduces, therefore, a new communication-theoretic view of wireless systems and offers new opportunities for optimization. In Fig. 3, the conceptual block diagram of a conventional point-to-point communication system and the corresponding block diagram under an SRE-based framework are illustrated. Under the conventional communication-theoretic framework, the system is modeled through transition probabilities that are not considered to be optimization variables. Under the SRE-based communication-theoretic framework, on the other hand, the system is modeled through transition probabilities that can be customized, thanks to the deployment of RISs throughout the environment and thanks to the possibility of controlling and programming the functions that RISs apply to the impinging radio waves. Therefore, the system model itself becomes an optimization variable, which can be jointly optimized with the transmitter and the receiver: Rather than optimizing the input signal for a given system model, one can now jointly optimize the input signal and the system.

SREs with and without joint encoding and modulation at the transmitter and at the RIS - In Fig. 3, in particular, three system models are illustrated. The first communication-theoretic model is referred to a conventional radio environment in which, via a feedback channel that provides the encoder with channel state information, the transmitter and receiver are jointly optimized, e.g., by designing appropriate transmit and receive channel-aware vectors. The second communication-theoretic model is referred to an RIS-empowered SRE in which the feedback channels from the receiver and the environment (e.g., the RIS) are exploited for optimizing the setup (i.e., configuration, state, or action) of the RIS besides the transmit and receive channel-aware vectors. In this case, therefore, the transition probabilities that describe the wireless environment can be customized by appropriately optimizing the state of the RIS. These first two communication-theoretic models are analyzed and compared in. The third communication-theoretic model is referred to an RIS-empowered SRE in which the state of the RIS is employed for customizing the wireless environment while at the same time encoding information jointly with the transmitter. In this setup, in particular, the transition probabilities of the wireless environment depend on both the state of the RIS, which affects the wireless channel, and the data s encoded by the transmitter on the state of the RIS. This setup is analyzed in, where it is proved that performing joint transmitter-RIS encoding yields, in general, a better channel capacity.

Communication model with state-dependent channels - From an information-theoretic standpoint, broadly speaking, the conventional block diagram in Fig. 3 is described by the conditional probability law of the channel output given the channel input. For example, a binary symmetric channel is a model for describing the communication of binary data in which the noise may cause random bit-flips with a given probability. In the context of SREs, the conditional probability law of the channel output given the channel input can be customized by using RISs. The wireless environment can be programmed to evolve through multiple states (or configurations) that depend on how the RISs shape the impinging radio waves. The possibility of controlling the possible states of operation of the wireless environment jointly with the operation of the transmitter and the receiver offers opportunities for enhancing the overall communication performance. The resulting communication-theoretic model well fits, therefore, the transmission of information through state-dependent wireless environments (or simply channels) that are generated by nature but that are controlled and affected by the communication system. The block diagram in Fig. 3 illustrates the case study in which the transmitter takes actions (i.e., it configures the operation of the RISs distributed throughout the environment) that affect the formation of the states of the environment. In general, the specific state of the wireless environment can be controlled by the transmitter, the receiver, or by an external controller that oversees the operation of portions or the entire network. In general, in fact, the operating state of the wireless environment depends on the configuration of all the RISs distributed throughout it, which can be jointly optimized for achieving superior performance. The block diagram of SREs well fits, therefore, a communication model with state-dependent channels, whose states are directly controlled by the communication system rather than being generated and being dependent only by nature.

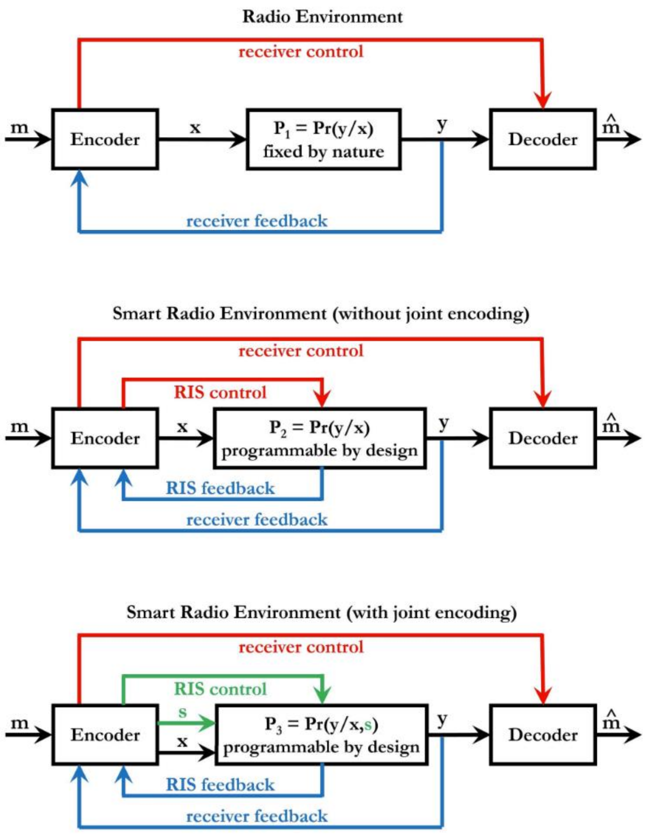

Fig. 3. Communication-theoretic models for radio environments and smart radio environments (with and without joint encoding)

Conclusion

Conceptually, the difference between current wireless networks and a smart radio environment can be summarized as follows. According to Shannon, the system model is given and is formulated in terms of transition probabilities. In a smart radio environment, the environmental objects are capable of sensing the system's response to the radio waves (the physical world) and feed it back to the input (the digital world). Based on the sensed data, the input signal and the response of the environmental objects to the radio waves are jointly optimized and configured through a software controller. New communication-theoretic models are needed for modeling, evaluating, and optimizing smart radio environments that leverage information theory, electromagnetic theory, and circuit theory.

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