

A Review of Reconfigurable Microstrip Patch Antennas

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Abstract: 5G/6G rapid development put forward new requirements on antenna size with multi-band in small volume, adaptive coverage, polarization diversity, MIMO operation and dynamic spectrum access. A promising solution is to employ reconfigurable microstrip patch antennas which modify the operating frequency, radiation pattern, polarization or a combination of these properties in one radiation structure. Recent advances on reconfigurable microstrip patch antennas for future wireless communication systems. In this paper, we give a literature review of recent advancements of the reconfiguration methods based on PIN diodes, varactor diodes, RF-MEMS switches, optical control, mechanical structures where these principles are applied in tuneable materials. It also discusses their applications in cognitive radio, 5G/6G terminals, MIMO systems, Internet of Things (IoT) devices, wearable electronics, and beam-steering arrays and satellite communication. This paper touches salient issues such as switching and conductor losses, parasitic effects on the low-frequency dynamics, DC-bias isolation (for magnetoelectric transducers), tuning range limitations, mutual coupling and performance variation with respect to different operating states.

Keywords: reconfigurable antenna; microstrip patch antenna; frequency reconfiguration; polarization reconfiguration; pattern reconfiguration.

Introduction Approaching from networks tailored to a relatively fixed set of licensed bands, wireless communication systems are evolving toward heterogeneous software-based platforms that must operate simultaneously across wide frequency ranges and cope with rapidly varying propagation and interference conditions. Fifth-generation (5G) systems integrate sub-6-GHz coverage and millimeter-wave capacity, while sixth-generation (6G) will include research on integrated sensing and communication, non-terrestrial connectivity, highly directional links/transmission lines/intelligent environments/adaptive radio access. This leads to conflicting requirements on the antenna, it must be small, cheap and yet operate over wide or multiband, high efficiency, polarization diversity, steerability, interference suppression and real-time adaptation. Conventional fixed antennas can only meet one specified operating condition, while the employment of multiple dedicated antennas would increase volume, coupling and feed complexity as well as cost.

Microstrip patch antennas have received significant interest for use in modern wireless devices due to their low profile, light weight, planar structure, conformability and compatibility with printed-circuit and monolithic integration [1-3]. The main limitations of these antennas are the narrow impedance bandwidth, moderate gain, surface-wave loss and sensitivity to substrate and fabrication tolerances. A more important note is that a conventional patch has stable electromagnetic features from manufacturing. This restriction can be addressed by modifying the antenna, more specifically by deliberately varying the proper current path, loading, feed condition, aperture distribution or material

properties [2-5]. As a result, one radiating structure may choose operating bands, switching between linear and circular polarization, main beam directing or several of them together.

Generally speaking, reconfigurable antennas can be classified as (i) frequency reconfigurable (ii) radiation-pattern reconfigurable (iii) polarization reconfigurable and (iv) compound reconfigurable antennas [1],[2], [5]. Frequency reconfiguration enables multistandard terminals and dynamic spectrum access (by band shifting or band selection). By varying the spatial distribution of radiation, pattern reconfiguration may enhance coverage, link quality, interference rejection and space reuse. With this technique, linear, right-hand circular and left-hand circular states can be switched among each other that reduces the polarization mismatch and multipath fading. Compound or multi-characteristic designs modify two or more functionalities, which provide better flexibility but necessitate more challenging switching, control and optimization. This functional classification is consistently used in major surveys, while stressing that practical performance strongly depends on the selected actuation mechanism [1]–[6].

Reconfigurable printed and microstrip antennas electrical switching is still the most popular physical implementation path for reconfigurable printed/microstrip antennas. Although the PIN diodes offer fast switching, small size integration, and low cost but they demand DC bias networks which adds resistance, package inductance and parasitic capacitance along with nonlinear effects. The tunability of varactor diodes is based on voltage-dependent capacitance, but deviated tuning linearity, quality factor, power handling and bias sensitivity can limit the realization. RF-MEMS generally achieves high isolation, low insertion loss and high-quality factor but may have higher actuation voltage, slower switching, packaging complexity, reliability issues and higher fabrication cost. While eliminating metallic bias lines helps optical switches to achieve excellent RF isolation, mechanical [1], fluidic [2], liquid-metal [4], phase-change [6], ferroelectric, graphene and other various types of tunable-material approaches provide their own trade-offs in tuning range, speed, loss, manufacturability and control complexity.

These mechanisms are especially invaluable in microstrip platforms where, by embedding switches (or reactive elements) across slots, stubs, parasitic patches, shorting paths, feed networks or defected ground structures to tailor the surface-current distributions. Nevertheless, a large simulated tuning bandwidth does not necessarily pertain to a better practical antenna. The electromagnetic model must incorporate the switching components and bias circuit; gain, efficiency, polarization purity, pattern stability, isolation, and power consumption for every state must be reported; simulated results need to be verified upon fabricated prototypes. At millimeter-wave frequencies, these requirements become increasingly challenging as the performance of component packages, interconnects, fabrication tolerances, radiation from bias-networks and losses in conductors and dielectrics may dominate.

This paper examines reconfigurable microstrip patch antennas from four closely related perspectives: the electromagnetic parameter being controlled, the mechanism used to achieve reconfiguration, the associated performance trade-offs, and the intended application. Its main contributions include: (i) a unified classification of frequency, radiation-pattern, polarization, and compound-reconfigurable microstrip antennas (ii) a comparative analysis of PIN diodes, varactor diodes, RF-MEMS switches, optical control, mechanical adjustment, fluidic techniques, and tunable materials (iii) an application-oriented

discussion covering cognitive radio, 5G/6G networks, MIMO systems, IoT and wearable devices, and satellite communication and (iv) the identification of research challenges related to compact bias-network integration, efficiency, reliability, multi-state measurement, intelligent control, programmable structures, and scalable antenna-array implementation. The paper presents antenna fundamentals and classification, reconfiguration mechanisms, open challenges and future research directions, followed by the conclusion.

Literature Methods

Based on the literature, reconfigurable antennas can be classified using two principal approaches:

1. According to the antenna characteristic being modified.

Reconfigurable antennas classified according to the electromagnetic characteristic being controlled. Frequency reconfiguration enables multiband operation and dynamic spectrum access, while radiation-pattern reconfiguration supports beam steering, wider coverage, and interference suppression. Polarization reconfiguration improves link reliability by reducing polarization mismatch and multipath effects. Compound or hybrid designs combine two or more of these capabilities, offering greater flexibility and adaptability for next-generation wireless communication systems [7-9].

Table 1. Classification of reconfigurable antennas

Sr. No	Reconfigurable antenna type	Parameter modified	Application
[1]	Frequency Reconfigurable	Resonant frequency or operating band	Multiband operation and dynamic spectrum access
[2]	Radiation-Pattern reconfigurable	Beam direction, beam shape, beamwidth or null position	Beam steering, coverage enhancement and interference suppression
[3]	Polarization reconfiguration	Linear, circular or elliptical polarization	Polarization diversity, reduced polarization mismatch and improved link reliability
[4]	Compound /Hybrid reconfigurable	Two or more characteristics combined	Multifunctional and adaptive operation in advanced wireless systems.

2. According to the mechanism used to achieve reconfiguration

Reconfigurable antennas can be broadly classified according to their tuning mechanism as electrically, optically, mechanically, and smart-material-based antennas[8-10].

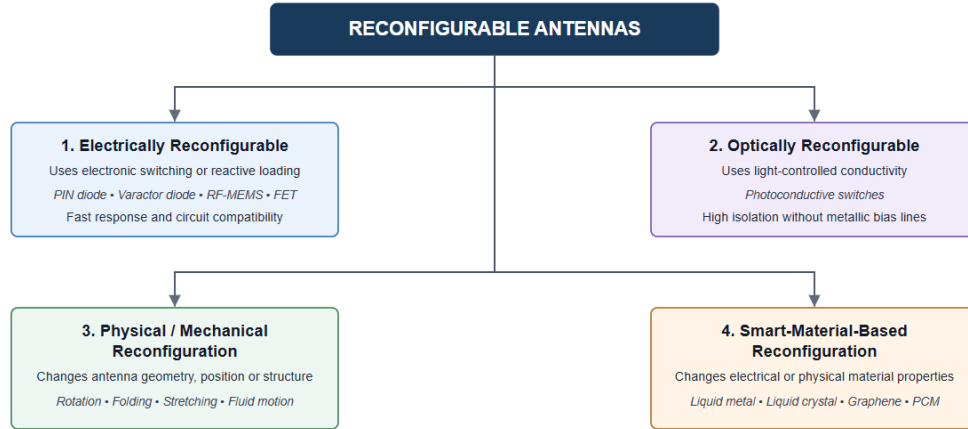


Figure 1. Classification based on the reconfiguration mechanism

All these mentioned categories in the figure 1, electrical tuning is by far the most common method for tuning microstrip patch antennas. This process can be achieved through the use of different switching and tuning elements depending on the needs of the antenna. The benefits and drawbacks of these elements are shown in Table 2 below.

Table 2. Comparison of Electrically reconfigurable methods

Component	Nature of control	Major advantage	Major limitation
PIN diode	Discrete ON/OFF switching	Fast, inexpensive and easy to integrate	Requires a DC-bias circuit and introduces parasitic effects
Varactor diode	Continuous capacitance variation	Continuous frequency tuning	Nonlinearity, limited power handling and bias sensitivity
RF-MEMS switch	Discrete switching	Low insertion loss and high isolation	High actuation voltage, cost and packaging complexity
Transistor/FET	Electrically controlled switching	Fast control and circuit integration	Loss, nonlinearity and additional biasing requirements

Electrically reconfigurable antennas performances are strongly dependent on such as the interaction between switching elements and antenna structures. Hence the needed number, position and ON/OFF states of the switches must be defined to ensure that desired operating modes can be achieved with limited degradation of radiation characteristics. For designs based on PIN-diode, the nonlinear behaviour of diodes and complex biasing networks may decrease antenna efficiency or radiation performance [10]. RF-MEMS switches can operate with low loss, have compatibly with rigid as well as flexible substrates but due to their high structural complexities and actuation requirements may suffer from making them less usable in low-power applications [10]. Optical switches do away with traditional metallic bias lines, but their performance is greatly influenced by the magnitude and profile of the activating light [10]. Thus, future works should be oriented towards more compact switching structures and bias networks, along with a systematic optimization of the location, number and states of operation of the switches.

Conclusions

This paper reviewed the major techniques used to realize reconfigurable antennas for next-generation wireless communication systems. The antennas were classified according to the parameter being controlled frequency, radiation pattern, polarization, or a combination of these and the mechanism used for reconfiguration. Electrical, optical, mechanical, fluidic, and smart-material-based approaches were discussed with their advantages and limitations. Among these methods, electrical reconfiguration using PIN diodes, varactor diodes, and RF-MEMS switches remains the most widely adopted because of its compact size, rapid response, and ease of integration. However, switching losses, parasitic effects, complex biasing networks, limited tuning range, and variations in radiation performance continue to present practical challenges. Future research should focus on compact multifunctional designs, low-loss switching components, simplified bias circuits, intelligent control, and reliable experimental validation.

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