

5G/6G를 위한 지능형 재구성 안테나 특허 동향

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권 동 승

이동통신연구본부
한구전자통신연구원

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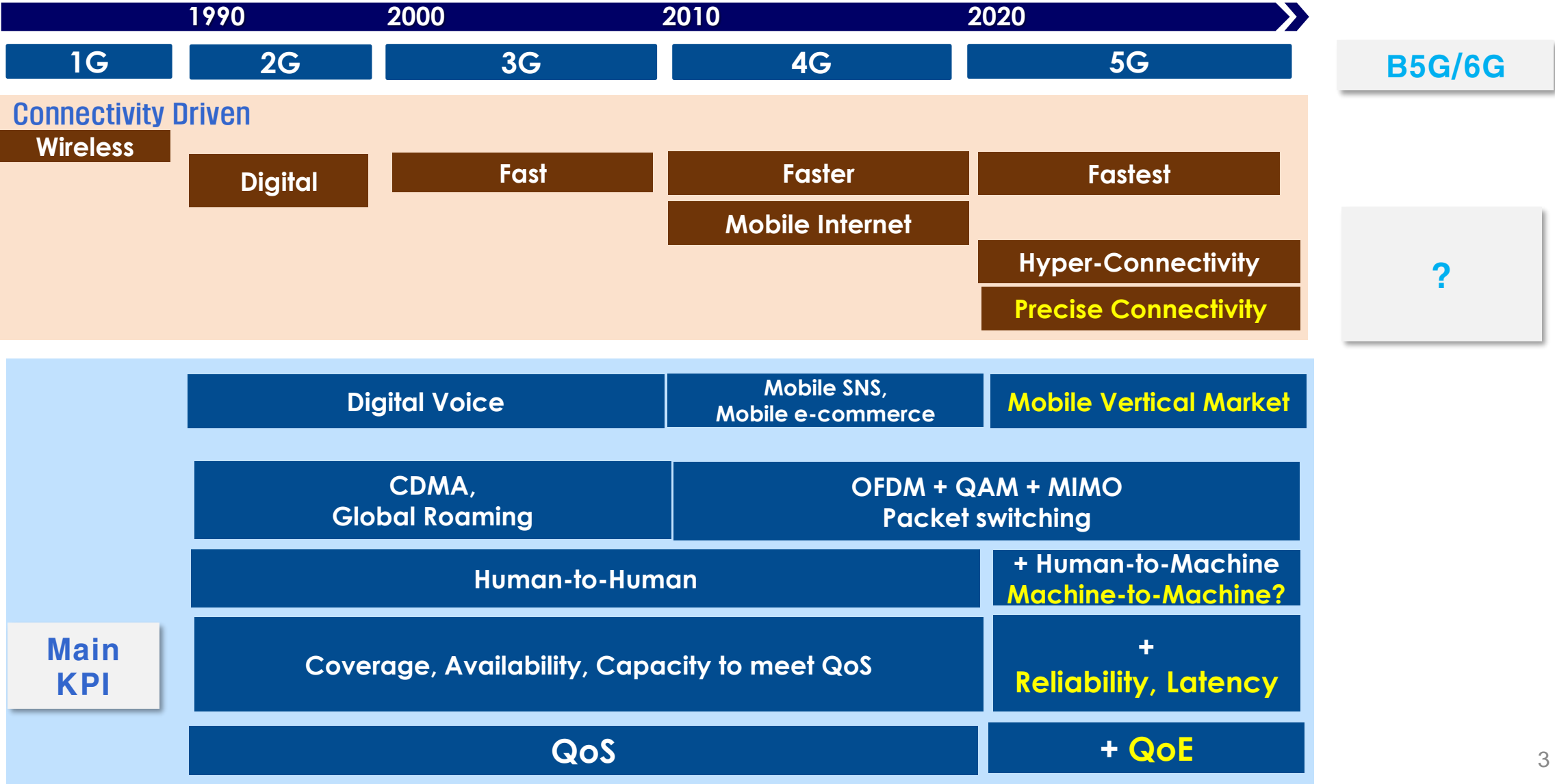
◆서론

◆Metamaterial, Metasurface

◆Reconfigurable Intelligent Surface

◆특허정보 조사 분석

▶ 이동통신 진화



▶ 무선채널

- 극복할 대상
 - Equalizer, Diversity, ...
- 활용할 대상
 - MIMO
 - Spatial modulation, media-based modulation
- 전파전파 특성을 조작 or/and 제어할 수 있을까?
 - Smart Radio Environment

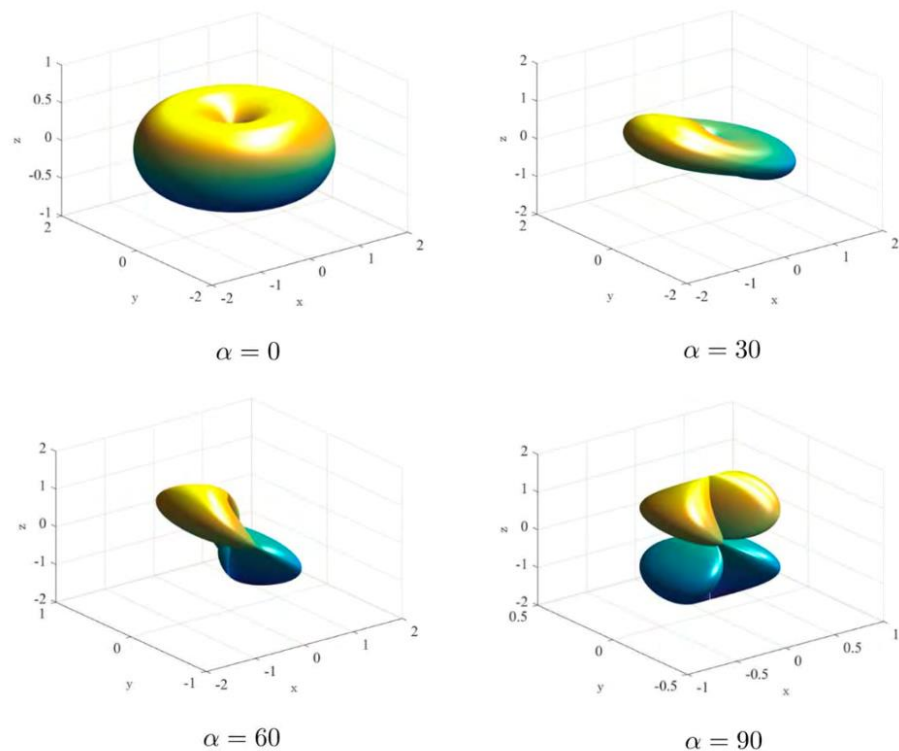
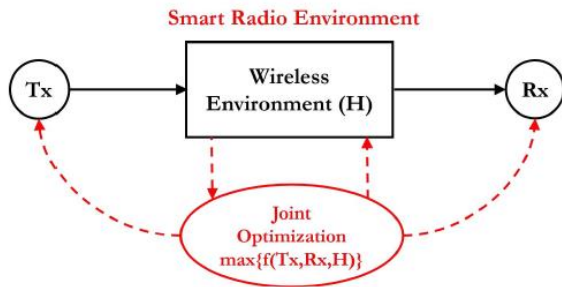
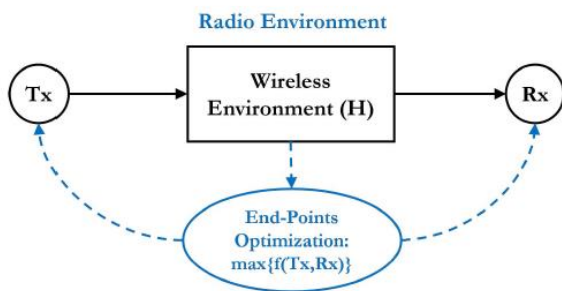
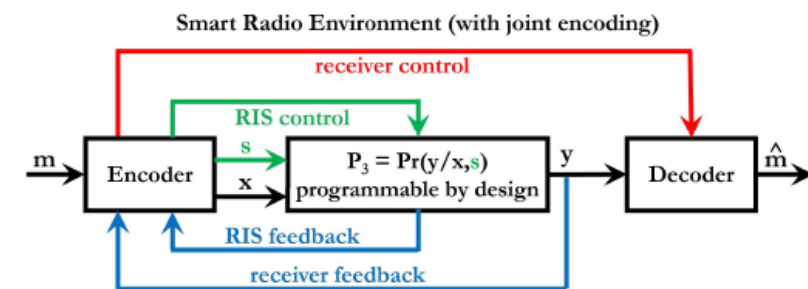
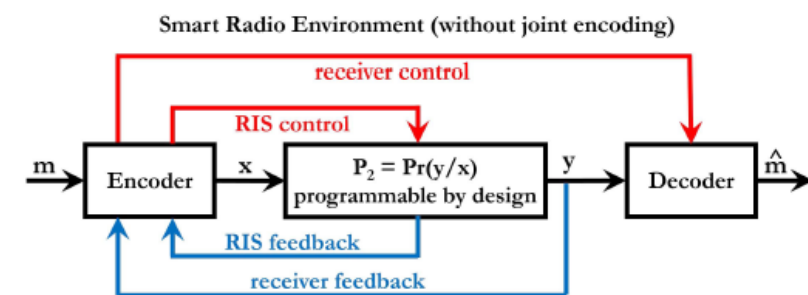
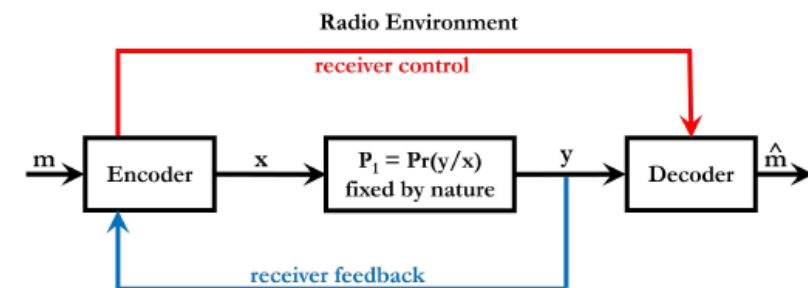


FIGURE 10. Example of different radiation patterns of a reconfigurable antenna (dipole). Two bits can be mapped into the realization of four different radiation patterns: "00" $\rightarrow \alpha = 0$, "01" $\rightarrow \alpha = 30$, "10" $\rightarrow \alpha = 60$ and "11" $\rightarrow \alpha = 90$.

◆ A smart radio environment (SRE) is a **wireless environment that is turned into a smart reconfigurable space** and that **plays an active role in transferring and processing information**.

- The wireless environment itself is turned into a **software-reconfigurable entity**,
 - whose operation is **optimized to enable uninterrupted connectivity, QoS guarantee**,
 - and where **the information is transmitted without necessarily generating new signals** but recycling the existing ones whenever possible.
- The **possibility of creating wireless systems with state-dependent channels opens new opportunities for overcoming some fundamental limitations in designing current wireless networks**.
 - The ultimate performance limits of wireless networks may not have been reached yet.
 - Customizing and controlling the wireless environment may open new opportunities for network optimization.
 - The radio waves may be used more efficiently.
 - The spatial capacity density may be increased.
- **How to tailor smart radio environments into the real world?**
 - **programmable frequency-selective surfaces**,
 - **smart reflect-arrays or mirrors in the environment**,
 - **embedding arrays of low-cost antennas into the walls of buildings**,
 - **coating the environmental objects with reconfigurable meta-surfaces**.



◆(Metasurface 기반 반사 및 투과 안테나 Prototype)

- MIT의 **RFocus prototype**와 NTT DOCOMO의 Smart glass prototype
— 랜덤한 무선채널에 대응하는 지능적 재구성 기능 없음

◆유럽에서 재구성 지능형 안테나(RIS: Reconfigurable Intelligent Surface) 프로젝트 → 초기 연구단계

- (2017년 1월 시작된 **VisorSurf**) **프로그래머블한 전자기적 동작 실현**을 위해 스마트하게 상호 연결된 평면에 대한 하드웨어와 소프트웨어 개발.
- (2019년 11월 시작된 **ARIADNE**) D-대역 (110~170GHz)에서 무선 환경 속의 물체를 RIS로 코팅하여 **제어 가능한 반사기로 전환시켜서 무선망에 향상된 연결성을 제공**하는 기술과 프로토콜을 개발.
- (2021년 1월 시작된 **RISE-6G**) RIS 적용한 6G 통신 연구. **RIS 설계, 채널 모델링, 사용자 체감 품질 및 위치 기반 서비스 향상 등** RIS 활용한 다양한 기술 개발 시작
- (2021년 5월 시작된 **PathFinder**) **Metasurface를 이용하여 무선환경을 SRE로 전환**시키기 위해 **통신 이론, 물리학, 전자기학의 다학제 방법론으로 RIS를 지원하는 무선망의 이론적·알고리즘 연구**

◆(S. Maci, "Present and future trends in metasurface antennas," in Huawei Technology Summit. Munich, Germany, Oct. 2019.)

- 랜덤한 무선채널에 대해 **Metasurface를 실시간 재구성할 수 있는 채널 추정, 자원 할당과 기계학습 등 연구 필요**



Fig. 2. MIT's RFocus prototype (photo: Jason Dorfman, CSAIL).

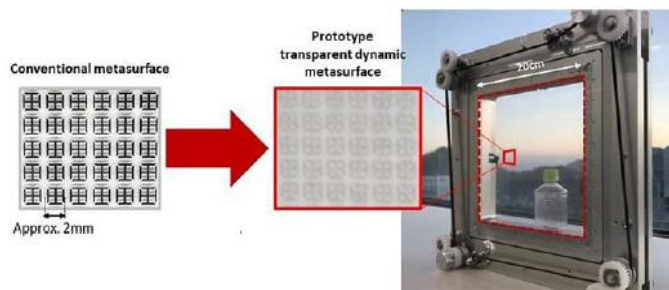


Fig. 3. NTT DOCOMO's prototype (photo: NTT DOCOMO).

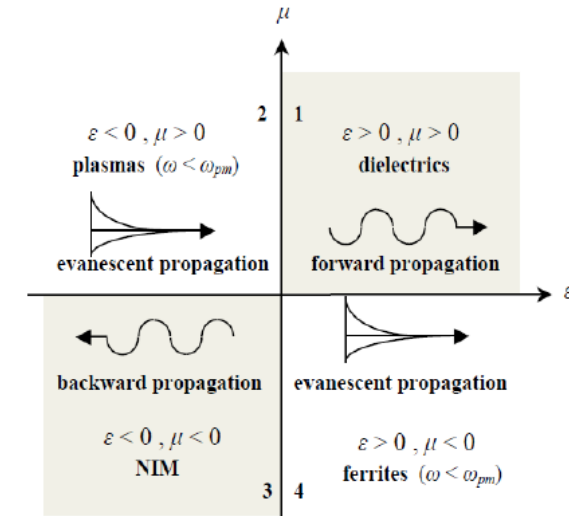


Smart space-time Metasurfaces can be the key-future technology for smart environment "beyond 5G"

Metamaterial, Metasurface

▶ (**Metamaterial**) 자연계에 존재하지 않는 물질로 빛, 소리 그리고 다른 많은 물리적 현상을 조작하고 제어하기 위해 **음의 유전율 or/and 음의 투자율**을 갖도록 인공적으로 설계된 물질

- Metamaterial is **an arrangement of periodic structures of unit cells** in which **the average size of a unit cell should be much smaller than the impulsive wavelength of the light**.
 - **materials with negative permittivity** below plasma frequency and **positive permeability** → **Artificial Dielectric**
 - **negative value of permittivity and permeability** . No such material is found in nature. → **Negative-Index Material**
 - **negative permeability** below plasma frequency and **positive permittivity**. It includes **ferrite materials**. → **Artificial Magnetics**
- Chronological development of metamaterials
 - (1904) Possibility of negative phase velocity accompanied by an anti-parallel group velocity were noted by Horace Lamb and Arthur Schuster
 - (1959) V.M. Agranovich and V.L. Ginburg reported repercussions of negative permittivity, permeability, and group velocity in their study of crystals and excitons.
 - (1968) V.G. Veselago first studied **the effect of negative permittivity and permeability has on wave propagation**.
 - (1996) John Pendry proposed **Split Ring Resonators (SRR)** to realize a **negative permittivity**.
 - (2000) David R. Smith is the **first in the world to realize that a medium with an effective negative index of refraction physically exists**.
 - (2006) At microwave frequencies, the **first real invisibility cloak** was realized.



Metamaterial, Metasurface

▶ (Metamaterial 안테나) leaky-wave antennas (LWAs)와 resonator-type small antennas.

● (LWAs) 유도된 전력이 전파의 방사 형태로 점진적으로 누출

- CRLH(composite right/left-handed) Transmission Line metamaterial로 구현된 LWA는 기존 LWA에서는 구현하기 어려운 브로드사이드 방사를 포함하여 후방에서 전방으로 빔 스캐닝을 가능하게 함

● Metamaterial 기반 공진형 소형 안테나

— CRLH 기반 혹은 분산 공진 안테나

- antennas with negative-order modes and zeroth-order resonators.

— Miniature antennas based on the metamaterial loadings, such as the ϵ/μ -negative materials, high μ shells, and the magnetic photonic crystals.

— Meta-공진 안테나: antennas based on the split-ring resonators (SRRs), complementary split-ring resonators (CSRRs).

- SRR can be considered as a resonant magnetic dipole which has been widely used to synthesize metamaterials.
- CSRR, originally introduced by Falcone et al. in 2004, has been proven to exhibit **negative permittivity**. It also has been considered to behave as an electric dipole.

— Antennas loaded with metasurfaces: electromagnetic band gap (EBG) mushroom structures, patch-type reactive impedance surface(RIS).

- They are able to **miniaturize the antenna size, reduce the surface wave** as well as to **improve the radiation characteristics**.
- RIS composed by periodic metallic patches, the mushroom-like high-impedance or artificial magnetic conductor (AMC) or EBG structures, and the uniplanar compact photonic band gap (UC-PBG) surface.

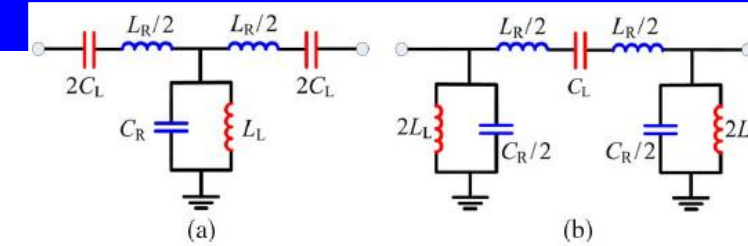


Fig. 1. Equivalent circuits for the symmetrical CRLH unit cells. (a) T-type model. (b) π -type model [21].

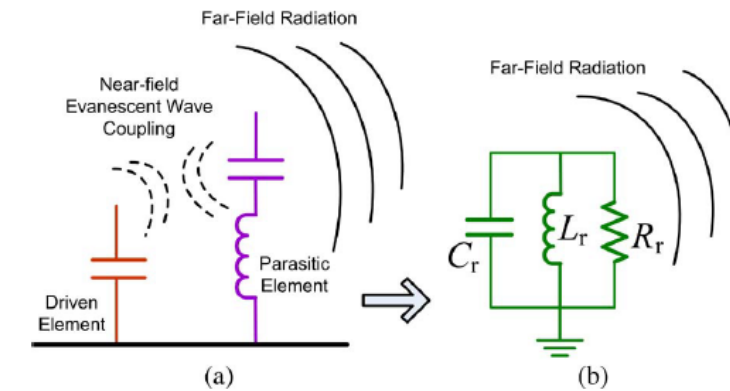
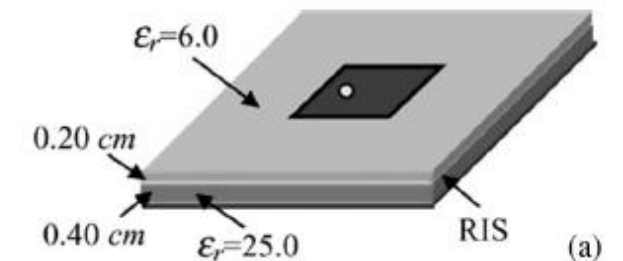


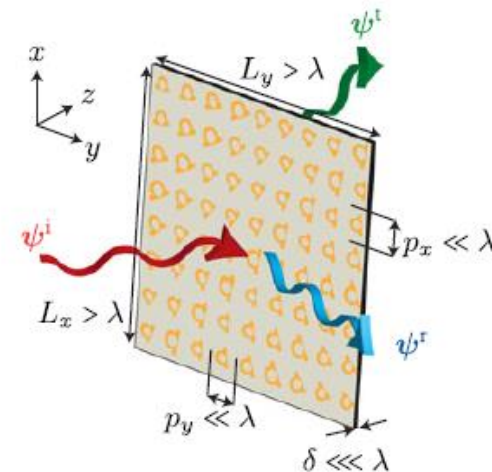
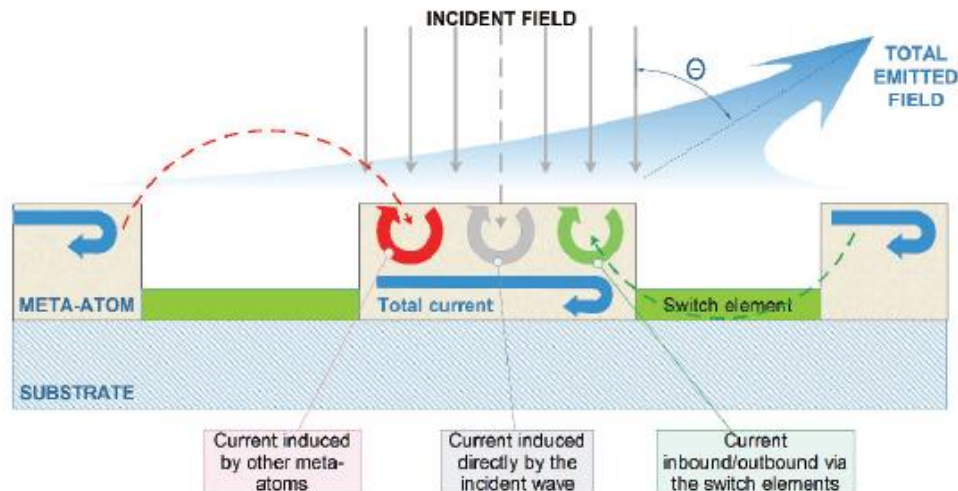
Fig. 10. (a) The coupling and radiation behavior of the near-field metamaterial-loaded small antenna. (b) Final RLC resonator approximation for the whole antenna.



Metamaterial, Metasurface

◆ (Metasurface) 두께는 파장보다 매우 작지만, 크기는 파장보다 매우 큰 2차원 평면에서 접지된 유전체 substrate 위에 파장보다 작은 길이의 금속 혹은 유전체 패치) 2차원 배열 구조

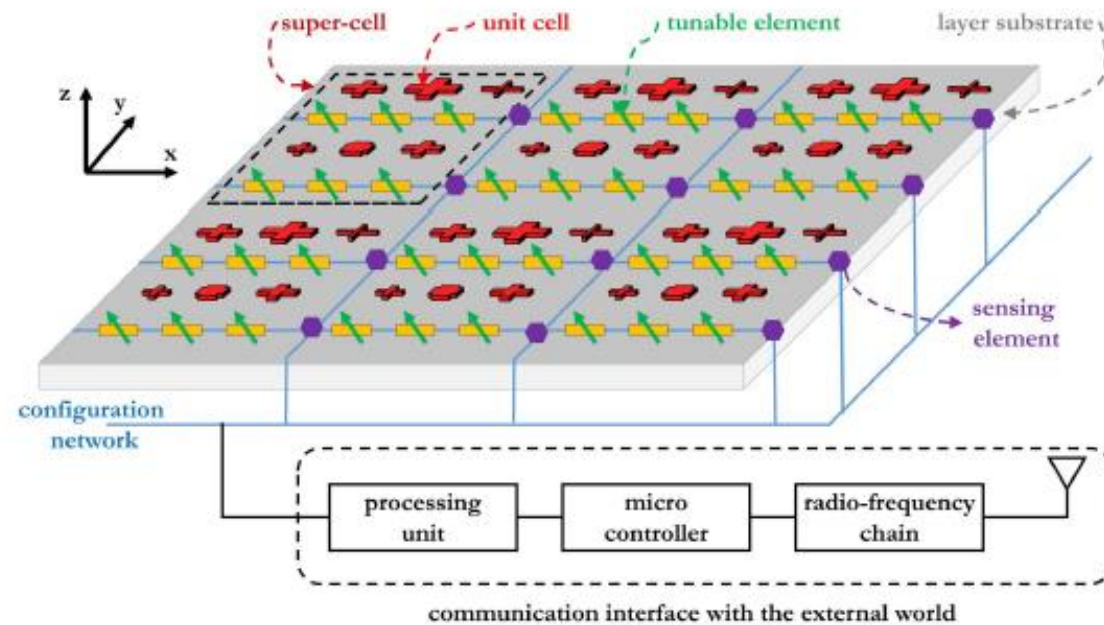
- General metasurface transforms an incident wave ψ_i into a reflected wave ψ_r and a transmitted wave ψ_t . A metasurface is typically an electrically very thin ($\delta \ll \lambda$), electrically relatively large ($L_x, L_y > \lambda$), homogenizable ($p_x, p_y \ll \lambda$) non-periodic, and bianisotropic electromagnetic structure.
 - An **electromagnetic meta-surface** is made of a **two-dimensional array of sub-wavelength metallic or dielectric scattering particles that transform the electromagnetic waves in different ways.**
 - The **major difference between a surface and a meta-surface** lies in **the capability of the latter of shaping the radio waves according to the generalized Snell's laws of reflection and refraction.** For example, the angles of incidence and reflection of the radio waves are not necessarily the same in a meta-surface.
- 입사 전자기파를 다양한 방식으로 변환시키는 기능(반사, 굴절, 흡수, 투과, focusing, 편파, splitting, 아날로그 처리, collimation, 변조, 다중 스트림, 인코딩 등 송신기) 가능.



Reconfigurable Intelligent Surface

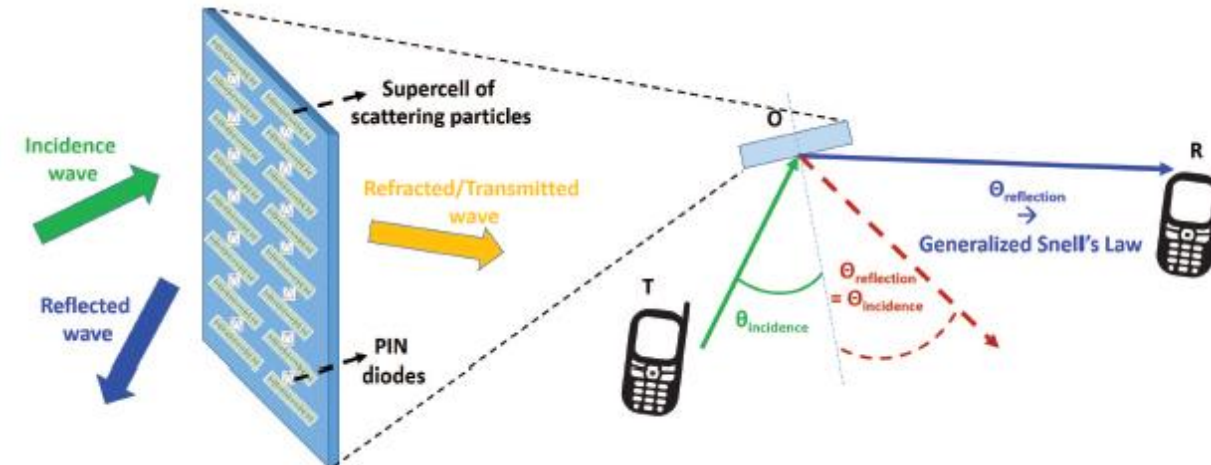
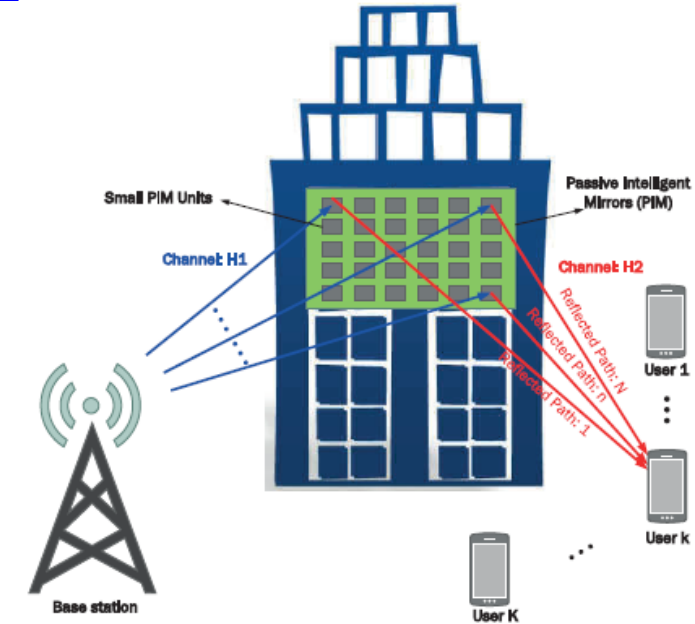
◆ (Reconfigurable Intelligent Surface, RIS) 랜덤한 무선채널 환경에 적응적으로 대처하기 위해 Metasurface 특성을 지능적으로 재구성한 2차원 평면 시스템

- Its transverse size is much larger than the wavelength of the radio waves (e.g., a few tens or a few hundreds times larger than the wavelength depending on the functions to realize), and its thickness is much smaller than the wavelength of the radio waves.
 - An RIS is referred to as a **zero-thickness sheet of electromagnetic material**.
- The RIS is constituted by **composite material layers that are made of metallic or dielectric patches printed on a grounded dielectric substrate**.
 - Each patch can be modeled as a **passive scattering element**, and is referred to as **unit cell** or **scattering particle**.
 - The size and inter-distance of the unit cells can be either of **the order of the wavelength (usually half the wavelength)** or can be **smaller than the wavelength (usually 5-10 times smaller than the wavelength)**.
 - The metasurface may **transform the incident electromagnetic (EM) fields into desired EM fields through appropriate, locally distributed, balanced absorptions and gains**.



Reconfigurable Intelligent Surface

- (Passive Intelligent Mirrors, PIM) a physical metasurface composed of many small-unit reflectors equipped with simple low-cost sensors and a cognitive engine.
 - Each unit of the mirror is able to reflect a phase-shifted version of an incoming electromagnetic field. Thus, by suitably designing the phase shifts, it is possible to constructively combine the signals reflected by the different units, which effectively makes the PIM an active medium.
 - A PIM is able to act as an **amplify-and-forward relay**.
- A **reconfigurable meta-surface** is a meta-surface in which the scattering particles are not fixed and engineered at the manufacturing phase, but can be modified depending on the stimuli that the meta-surface receives from the external world.
 - **Multiple elementary scattering particles** that realize some specific wave transformations can be connected by using electronic circuits that activate only those that synthesize the specified wave transformation of interest for a given network configuration. This functionality is, e.g., realized by using PIN diodes.
 - The European-funded project **VISOR-SURF** have recently built the **prototype of a software-controlled meta-surface** that makes the wireless environment fully reconfigurable.



Reconfigurable Intelligent Surface

- (smart reflect-arrays) By optimally controlling the phase shift of each element on the reflect-array, the useful signals for each transmission pair can be enhanced while the interferences can be canceled.
 - Multiple wireless users in the same room can access the same spectrum band at the same time without interfering each other.
- The programmable metasurfaces enable us to benefit from multiple unique functionalities controlled by external stimuli.
 - The tailored unit cell structures of metasurfaces have been showing powerful abilities in achieving perfect absorption, anomalous reflection, focusing, imaging.
 - The properties of the metamaterials and metasurfaces can be adjusted by adding “tuning” capability in the unit cells. → Their electromagnetic wave behavior can be tuned externally by modifying the stimuli. Such tuning can be controlled by a computer program.
 - (Towards software-defined metasurfaces) A more elaborate way in making tunable metasurfaces is to have the tunability in the change of the unit cell structural configurations.
 - By controlling the connectivity at different locations, reconfiguration of the structure is obtained, thus providing multiple and tunable functionalities.
 - One challenge resides in the development of a platform that allows users to easily characterize and reconfigure the metasurface.

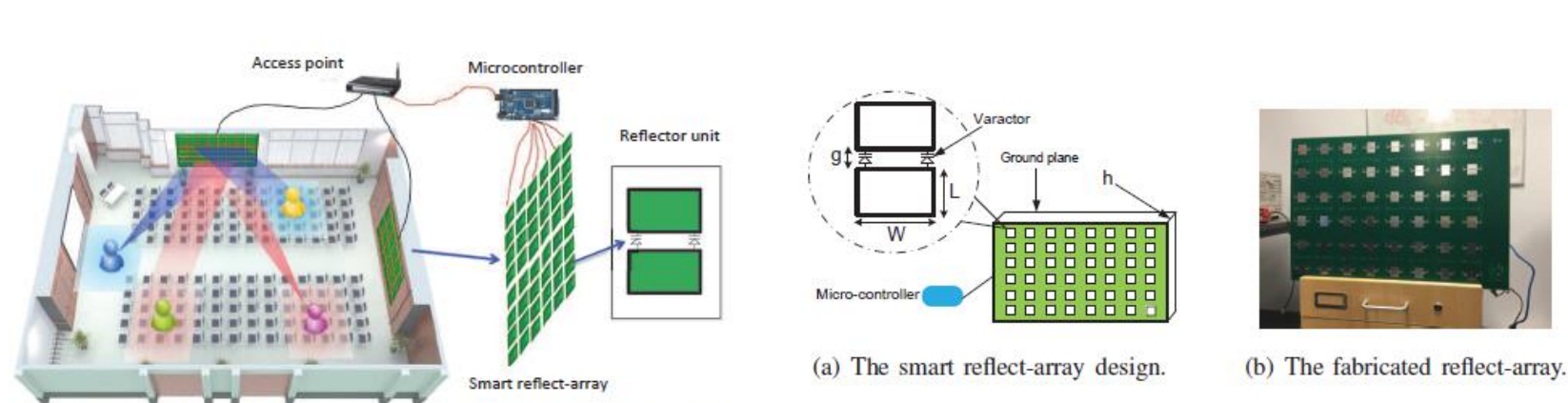
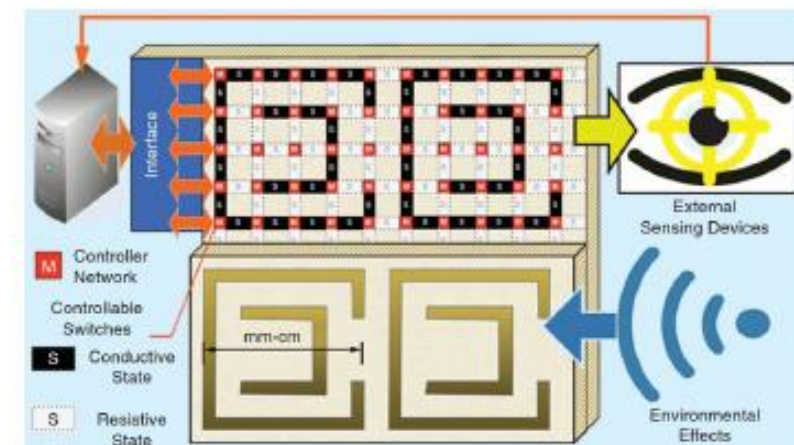


Fig. 2. Testbed design of the smart reflect-array.



Reconfigurable Intelligent Surface

- (Large Intelligent Surfaces, LISs) LISs are useful for constructing an intelligent and active environment with integrated electronics and wireless communications where each part of an LIS can send and receive electromagnetic fields.
 - Mutual coupling effects and antenna correlations can be easily avoided, such that sub-arrays are large and the channel is well-conditioned for propagation. Thus, LISs can be realized via **Ultra-Massive MIMO (UM-MIMO)**.
 - LISs are **very useful for applications with low-latency**, because channel estimation techniques and feedback mechanisms that LISs support are simple.
- (Intelligent Reflecting Surfaces, IRSs) IRSs will be utilized in 6G, because they foresee that wireless networks will be smart radio environments which are potential to realize uninterrupted wireless connectivity and use existing radio waves to transmit data without generating new signals.
 - The highly probabilistic wireless channel is **tuned into a deterministic space** by using the software-controlled propagation of the EM waves in the smart radio environment realized by IRSs. IRSs help to **enhance the communication between a source and a destination by reflecting the incident wave**. By adjusting the reflection coefficients at the IRS, IRSs enable the reflected signals being coherently added to the receiver without adding additional noise.
 - IRSs can **modify the signal phase and increase signal power**. In particular, by utilizing local tuning, graphene-based plasmonic reconfigurable metasurfaces can obtain some benefits, including **beam focusing, beam steering, and control on wave vorticity**.
 - Unlike LISs, IRSs use passive array architecture for reflecting purpose.

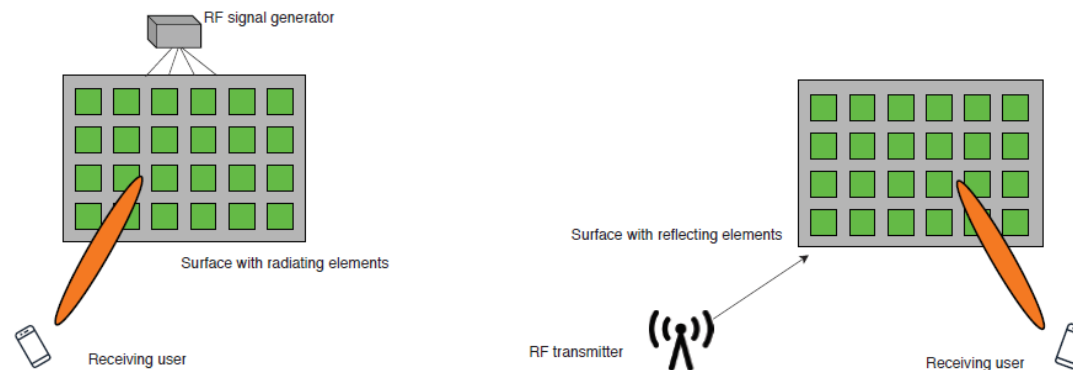
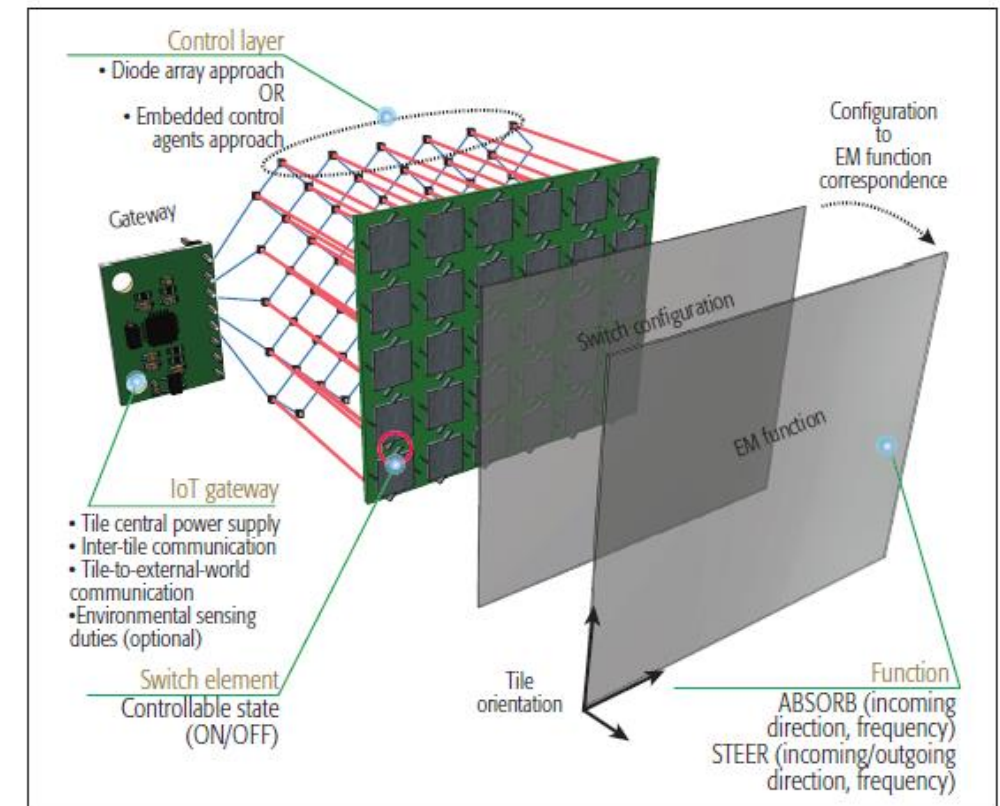
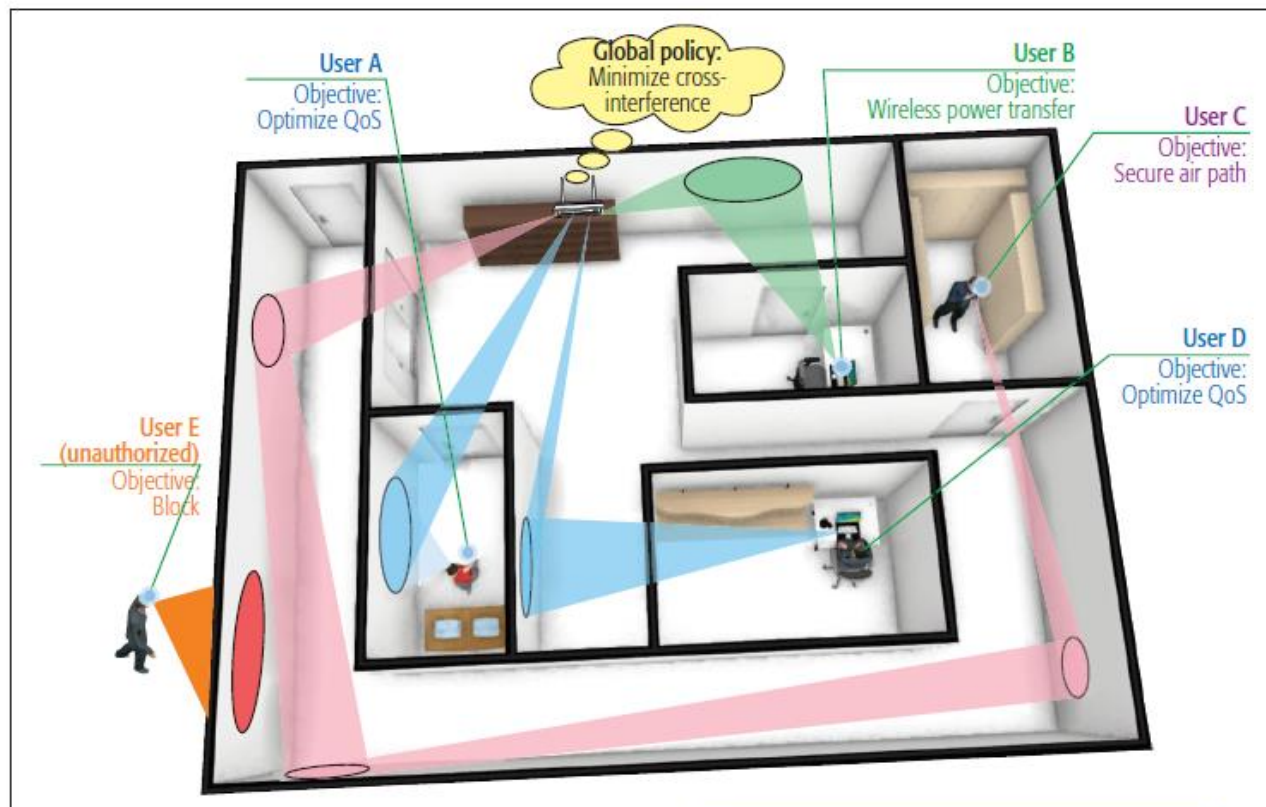


Fig. 5. Left: Large Intelligent Surfaces (an RF signal generator locates at the backside). Right: Intelligent Reflecting Surfaces (an RF signal generator locates at another location).

Reconfigurable Intelligent Surface

● Programmable Wireless Environments by HyperSurface

- Consider a scenario of wireless communications within a space. Users A and D are interested in [optimal connection quality](#), user B is interested in [wireless power transfer](#), and user C requires [eavesdropping avoidance measures](#). Finally, user E represents [unauthorized access or interference attempts](#), which may be deliberate or random.
- A [HyperSurface tile](#) is envisioned as a **planar, rectangular structure that can host metasurface functions over its surface with programmatic control**. It comprises a stack of virtual and physical components

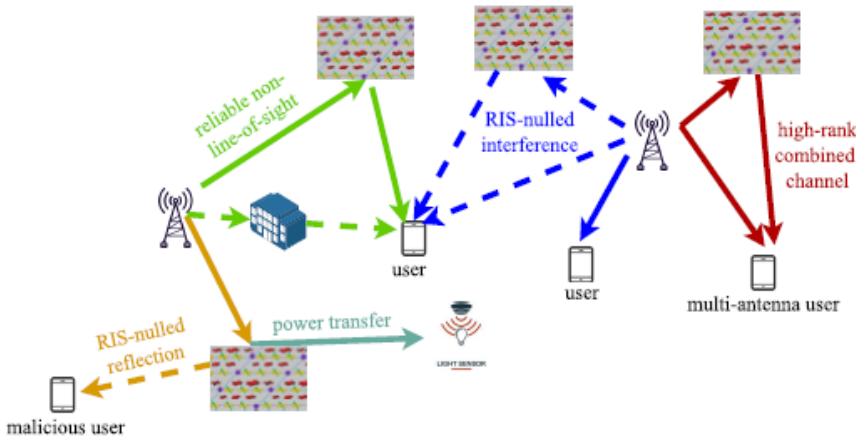


Reconfigurable Intelligent Surface

Potential Application

► Potential applications of Reconfigurable Intelligent Surfaces in Smart Radio Environments

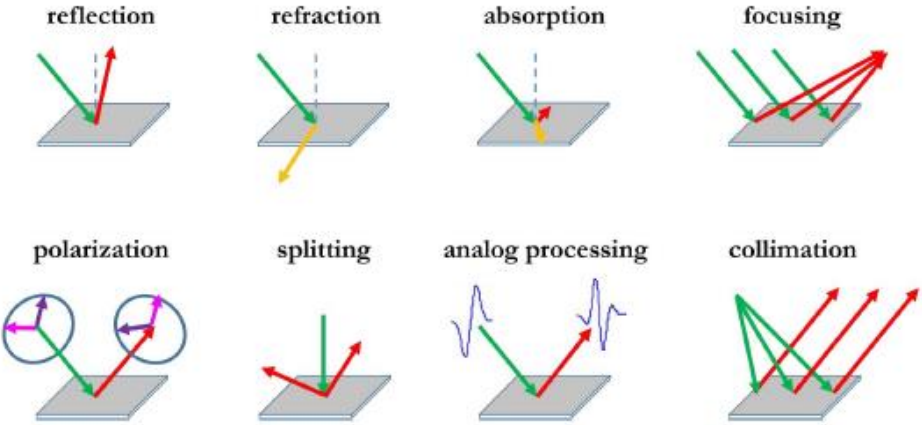
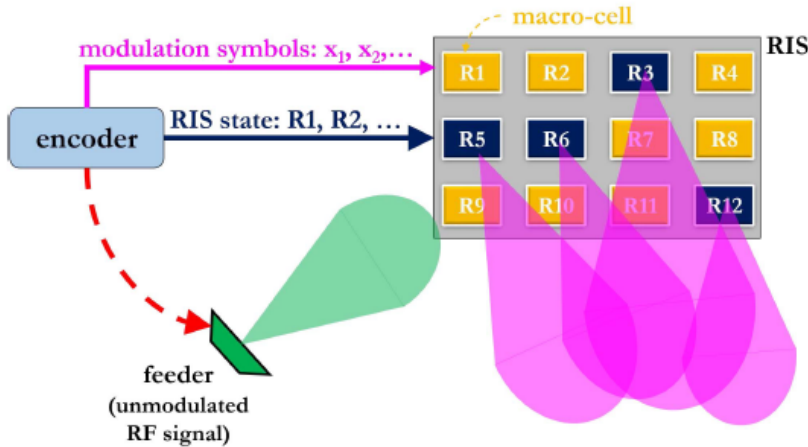
Applications	Descriptions
Coverage enhancement	An RIS can be configured in order to create adaptable non LoS links in deadzone (or low coverage) areas in which LoS communication is not possible or it is not sufficient.
Interference suppression	An RIS can be configured to steer signals towards specified directions or locations not only for enhancing the signal quality, but for suppressing unwanted signals that may interfere with other communication systems.
Security enhancement	This application is similar to interference suppression, with the difference that an RIS can be configured to worsen the signal detected by eavesdroppers by either creating destructive interference or by altering the reflection of signals towards locations not occupied by unauthorized users.
Channel rank enhancement	The spatial multiplexing gain that can be achieved in multiple-antenna systems depends on how well conditioned the channel matrix is. An RIS can be appropriately configured in order shape the wireless environment in a way that the channel matrix has a high rank and a condition number close to one, so as to increase the channel capacity.
Focusing enhancement	An RIS of large geometric size (in further text referred to as electrically large RIS) can operate in the radiative near-field at transmission distances up to a few tens of meters. Therefore, the scattered radio waves can be focused towards spatial spots of narrow size, so as to capillary serve dense deployments of users without creating mutual interference.
Radio localization enhancement	The high focusing capabilities of RISs of large geometric size can be capitalized for finely estimating the location of mobile terminals and devices, so as to support high-precision ranging, radio localization, and mapping applications.
Information and power transfer	The high focusing capabilities of RISs of large geometric size can be exploited for concentrating the energy towards tiny and energy-autonomous sensor nodes, so that the radio waves can be employed, simultaneously, to recharge the sensors and to transmit information.
Ambient backscattering	Consider a low power sensor node that is embedded into a smart surface for environmental monitoring. Any time that a radio wave impinges upon the smart surface, the RIS may be configured to modulate/encode the data sensed by the low power sensor into the scattered signal, e.g., by transmitting the sensed data through the time-domain scattered waveform (see Fig. 5). This enables low power sensors to piggyback information into ambient radio waves without creating new radio signals and, de facto, by recycling existing radio waves for communication [24], [25].



Reconfigurable Intelligent Surface

Potential Application

► Applications of Reconfigurable Intelligent Surfaces in Wireless Networks

EM-based design of RISs	Communication-based design of RISs
<p>These functions correspond to elementary transformations of the radio waves that can be directly specified at the EM level.</p> <p>Communication engineers view RISs as black boxes in which some parameters (knobs) can be optimized for improving the network performance.</p>	<p>For a communication engineer, a fundamental question may be: What is the optimal design or use of an RIS in order to maximize the channel capacity?</p> <p>The functions of RISs are not specified a priori, but they are the result of an optimization problem and may be different depending on the performance metric of interest.</p> <p>For example, RISs may be employed for realizing advanced modulation and coding schemes by directly operating at the EM level.</p>
<div><p>Fig. 5. Electromagnetic-based elementary functions.</p></div>	<p>(Metasurface-based transmitters) An RIS is viewed as an integral part of a transmitter.</p> <p>RIS based modulation: a metasurface-based version of spatial modulation and index modulation</p> <p>RIS-based multi-stream transmitter: metasurface-based version of multi-antenna spatial multiplexing</p> <p>RIS based-encoding</p> <div></div>

Reconfigurable Intelligent Surface

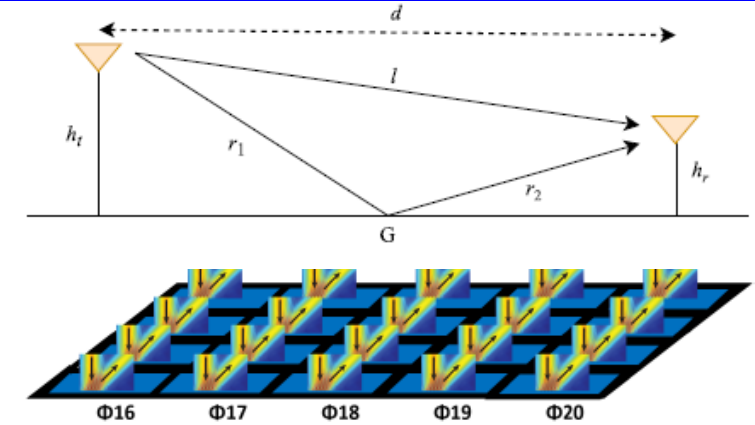
Potential Application: Coverage Enhancement

◆ Coverage Enhancement

- The Two-ray system model with an RIS made of many reconfigurable meta-surfaces

- A simple RIS example is made of **meta-surfaces that act as programmable reflectors**.
 - Assume that the ground floor is coated with an RIS that is **made of N reconfigurable meta-surfaces** each of which capable of tuning the angle of reflection according to the Snell's law and the phase of the reflected ray independently of the other meta-surfaces.

- By direct inspection of (7), two major conclusions can be drawn from $P_r \approx (N + 1)^2 P_t \left(\frac{\lambda}{4\pi d} \right)^2$.
 - 1) **the received power is proportional to N^2** , which is the number of phases of the RIS that can be controlled independently,
 - and 2) **the received power decays with the inverse of the square of the distance** between the transmitter and the receiver.



Reconfigurable Intelligent Surface

Potential Application: Coverage Enhancement (9/)

► RIS-Mediated Propagation

- The radiation density clearly exposes **different behaviors** for the **array near-field** and its **far-field region**.
 - The **array far-field region** unsurprisingly exposes a **path-loss related to r^{-4}** in both the linear and planar configurations.
 - The **array near-field** exposes a seemingly oscillatory behavior around **r^{-2} and r^{-3}** for the planar and linear configurations, respectively.
- It becomes **desirable to remain within the array near-field region**, which enlarges with frequency for an IRS of fixed physical dimensions as exposed in Table I.
 - The latter becomes specially appealing to **improve the RIS coverage with increasing frequency (e.g. for mm-wave) where diffraction is strongly compromised**.

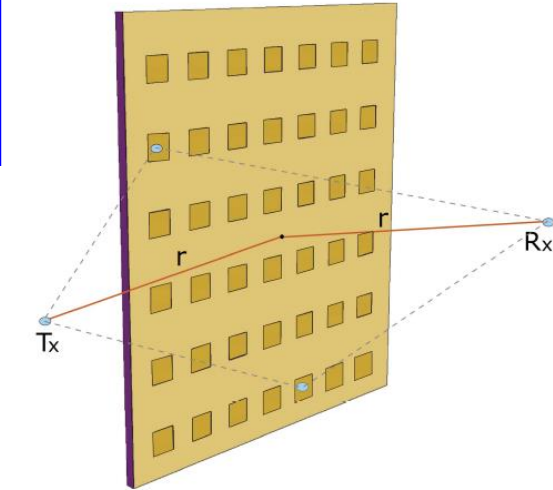


Fig. 2. Schematic view of Tx, Rx and RIS.

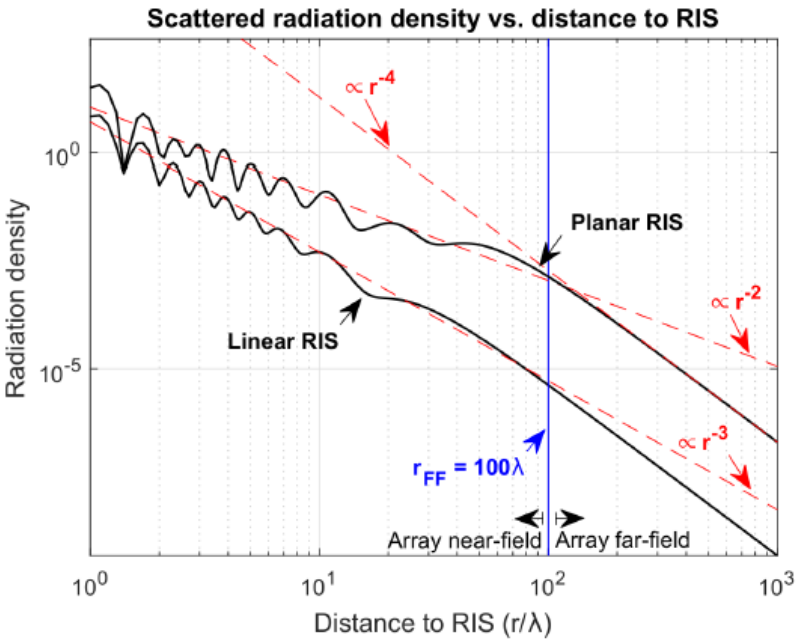


Fig. 3. Radiation density (power per unit area) of the field scattered by RIS versus distance for the setup of Fig. 2.

TABLE I

ARRAY FAR-FIELD LIMIT r_{FF} FOR A 1m^2 -SIZED RIS OVER SEVERAL FREQUENCIES OF OPERATION

Frequency of operation	Array near-field limit r_{FF}
800 MHz	2.6 m
1.9 GHz	6.3 m
2.4 GHz	8.0 m
5.8 GHz	19.3 m
10 GHz	33.3 m
28 GHz	93.3 m
60 GHz	200 m

Reconfigurable Intelligent Surface Modulation

◆ Programmable metasurface-based RF chain-free 8PSK wireless transmitter

- The programmable metasurface utilized in our transmitter has been elaborately designed to have a full 360° phase response and its reflectivity is about 85% at the working frequency of 4.25 GHz.

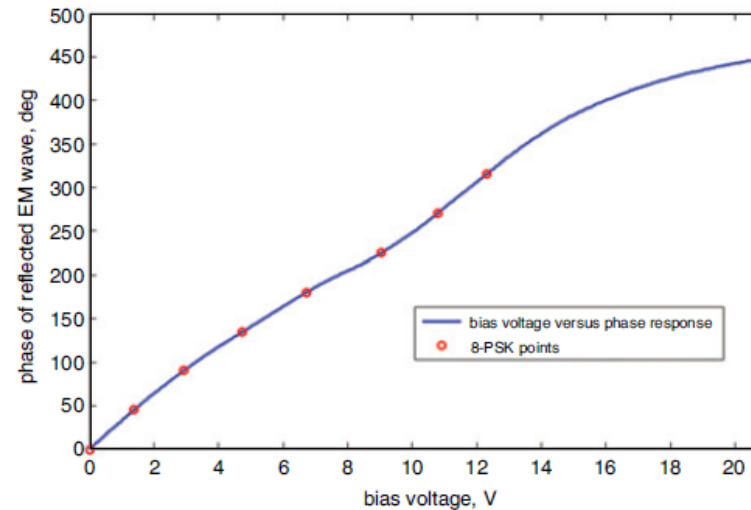
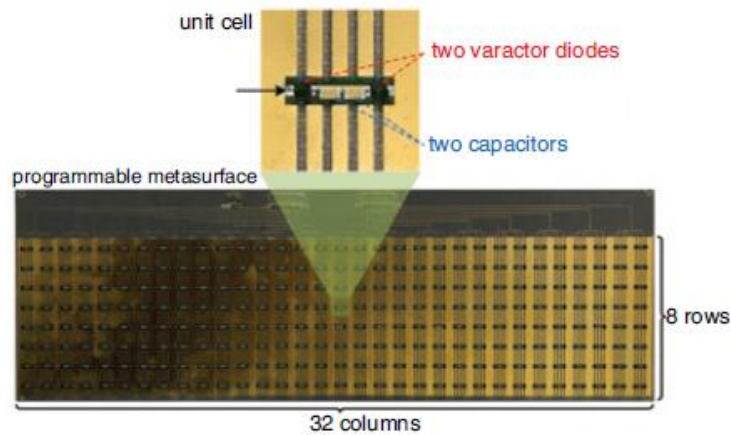


Fig. 3 Relationship between the bias voltage and the phase of the reflected electromagnetic wave

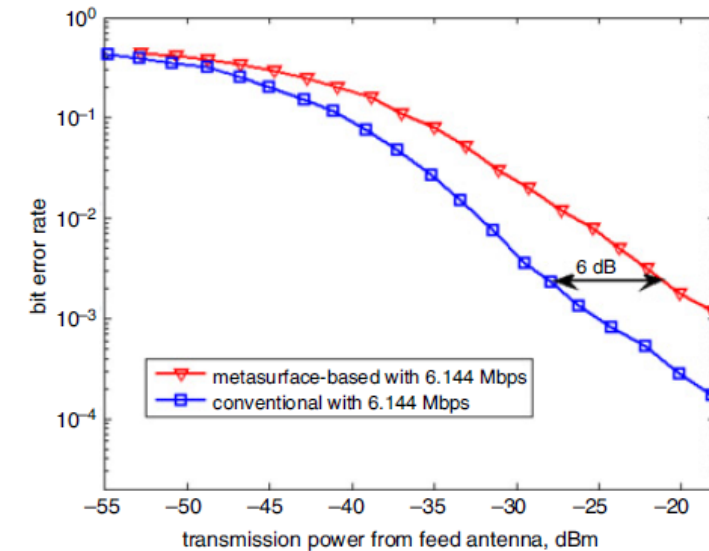


Fig. 8 BER versus transmission power

특허정보 조사 분석

▶ 사용 DB: WIPS

▶ 검색식: (메타머티리얼 or metamaterial or 메타표면 or metasurface) AND (안테나 or Antenna or 공중선 or 공중선유도체 or 방사체) AND (모바일* or 무선* or 통신* or mobile* or wireless* or radio* or telecommunicate*)

- 검색된 특허 수: 381건
- 노이즈 제거한 특허 수: 208 건 (PCT, 미국, 유럽, 중국, 일본, 한국에 출원된 특허 수, 중복 출원 포함)
- 요약, 주요 청구항 등 정성분석으로 핵심 특허 선정
 - 유효 특허 145
 - 핵심 특허 63
- 검색된 특허 기반으로 기술 분류
 - 대분류 (3건): Metamaterial 안테나, Metasurface 안테나, 시스템 및 무선부품
 - 중분류 (6건): Metamaterial 안테나 (2), Metasurface 안테나 (2), 시스템 및 무선부품 (2)
 - 소분류 (17건): 용도 별로 기술 분류
 - 세부 기술: 용도를 실현하는 구체적인 핵심 기술 keyword로 구분

특허정보 조사 분석

▶ 용어 정의

	정의	이슈
Metamaterial 안테나	<p>소형 안테나에서 기본 성능 개선을 위해 음의 유전율 or/and 투자율을 갖는 안테나</p> <p>※ 기본 성능: 광 대역폭과 다중대역, 방사 이득 · 효율 · 방향과 빔 스캐닝, 소형화</p>	<ul style="list-style-type: none"> - 소형화는 더 이상 문제가 아니므로, 광 대역폭과 고 효율성 확보 - Low-loss homogeneous Metamaterial 실현
Metasurface 안테나	<p>안테나의 기본 성능 개선과 더불어 변조, 투과 등을 실현하도록 전기적 파장보다 매우 큰 가로와 세로 길이, 파장보다 매우 작은 두께, 주기적으로 배치된 방사 요소간 간격은 파장보다 매우 작은 평면 안테나</p>	<ul style="list-style-type: none"> - 반사 · 굴절 · 투과 · 차단 · 변조 등 정적 제어
Metasurface 기반 RIS	<p>전기적 파장의 통상 수십 배 이상의 가로와 세로 크기, 전기적인 두께가 거의 0에 가까우며, 주기 혹은 비주기적으로 배치된 방사 요소간 간격도 전기적 파장보다 훨씬 작은 Metasurface(접지된 유전체 기판에 인쇄된 금속 또는 유전체 Patch로 구성된 복합 재료층의 2차원 구조)와 무선환경 변화에 실시간으로 지능적 대응할 수 있는 지능형(프로그램머블 혹은 기계학습 적용) 재구성 안테나 혹은 지능형 기지국.</p>	<ul style="list-style-type: none"> - 임의의 반사 · 굴절 · 투과 · 차단 등 실시간 동적 제어 - 무선 환경의 동적 변동에 대응하기 위해 무선 채널 응답에 능동적으로 적응하는 재구성 가능성 - 비용·에너지 효율적으로 실현하면서 효율적인 채널상태 정보 추정과 전달에 필요한 프로토콜과 알고리즘.

특허정보 조사 분석

▶ 기술 분류

대분류	중분류	소분류	목적 또는 기능 또는 효과
Metamaterial 안테나	Metamaterial 안테나	Metamaterial 안테나	Metamaterial을 이용한 안테나 기본 성능 (광대역/소형화/고이득/빔 형성/편파) 개선 기술
		단말기 Metamaterial 안테나	Metamaterial을 이용한 단말기용 안테나 기본 성능 개선 기술
	Metamaterial 어레이 안테나	Metamaterial 어레이/MIMO 안테나	Metamaterial을 이용한 안테나 어레이/MIMO 기본 성능 개선 기술
		단말기 Metamaterial 어레이 안테나	Metamaterial을 이용한 단말기용 안테나 어레이/MIMO 기본 성능 개선 기술
		변조용 Metamaterial 어레이 안테나	Metamaterial 어레이 안테나를 이용한 채널 변조 기술
		Metamaterial Reflector 안테나	Metamaterial 어레이 안테나를 반사기로 응용 한 기술
		Metamaterial Liquid Crystal 어레이 안테나	Liquid Crystal기반 Metamaterial 어레이 안테나 기술
		홀로그래픽 Metamaterial 어레이 안테나	홀로그래픽 기술을 Metamaterial 어레이 안테나에 적용한 기술
		기계학습기반 Metamaterial 어레이 안테나	기계학습을 Metamaterial 어레이 안테나에 적용하여 지능적 재구성 기술
		Metamaterial Lens 안테나	고 이득, 빔 형성, 다중 빔/빔 스티어링 등 실현 하는 Metamaterial Lens 안테나 기술
Metasurface 안테나	Metasurface 안테나	Metasurface 안테나	Metasurface를 이용한 안테나 기본 성능 개선 기술
		변조용 Metasurface 안테나	Metasurface 안테나로 주파수를 변조 기술
		Transparent Metasurface 안테나	전파를 투과시키는 Metasurface 안테나 기술
		홀로그래픽 Metasurface 안테나	홀로그래픽 기술을 Metasurface 안테나에 적용 기술
	지능형 Metasurface 안테나	지능형 Metasurface 안테나	Metasurface 안테나/reflector의 MIMO, 다중 빔 등 재구성에 지능화 적용 기술
시스템 및 부품	Metasurface 기지국	지능형 Metasurface 기지국	기계학습 등 적용으로 Metasurface 기지국 안테나/Relay 지능화 기술
	Metamaterial 무선 부품	Metamaterial 무선 부품	무선 부품(duplexers, combiners, dividers, 다중 안테나 급전장치 등)의 성능 개선 기술

특허정보 조사 분석: 정량 분석

▶ 분류 기술별 특허 정량 분석

— PCT, 미국, 유럽, 중국, 일본, 한국에 출원/등록된 특허 수, 중복 출원 포함

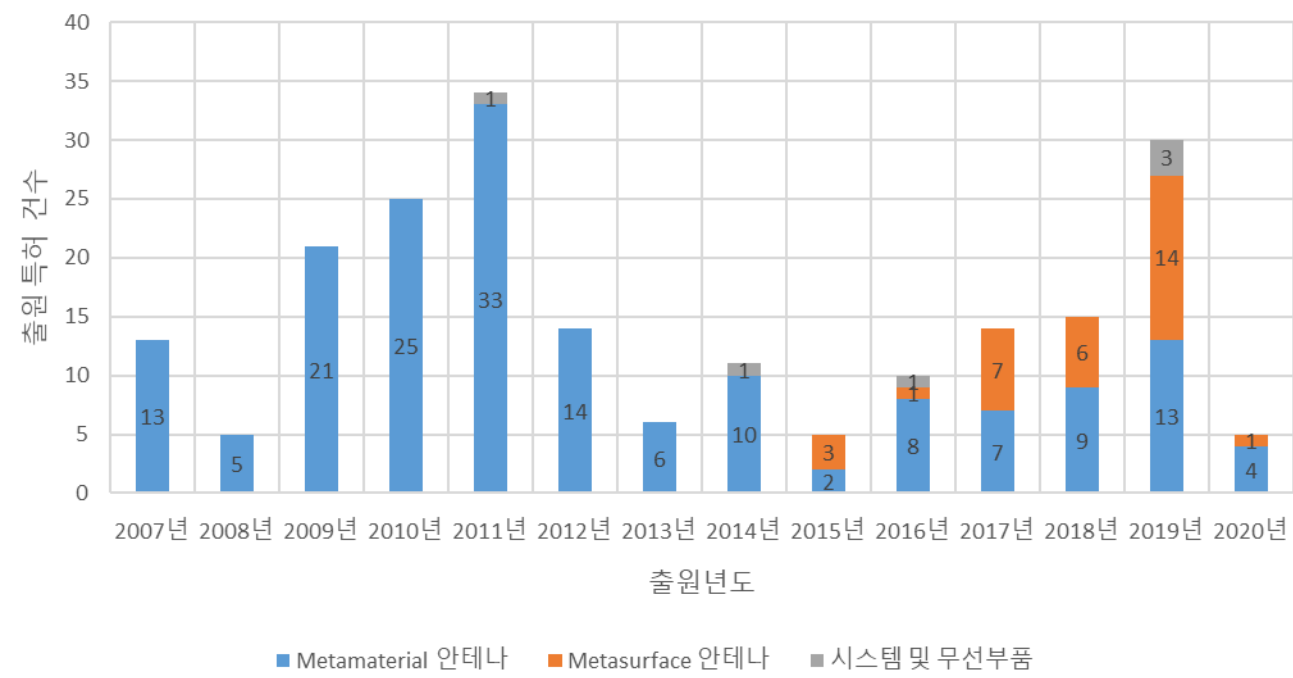
대분류	중분류	소분류	개수	비율
Metamaterial 안테나 (170건, 81.6%)	Metamaterial 안테나 (97건, 46.6%)	Metamaterial 안테나	69	33.2%
		단말기 Metamaterial 안테나	28	13.4%
	Metamaterial 어레이 안테나 (73건, 35.0%)	Metamaterial Lens 안테나	14	6.7%
		Metamaterial Liquid Crystal 어레이 안테나	4	1.9%
		Metamaterial 어레이/MIMO 안테나	41	19.7%
		기계학습기반 Metamaterial 어레이 안테나	4	1.9%
		단말기 Metamaterial 어레이 안테나	2	1.0%
		반사 Metamaterial 어레이 안테나	4	1.9%
		변조용 Metamaterial 어레이 안테나	3	1.4%
		홀로그래픽 Metamaterial 어레이 안테나	1	0.5%
Metasurface 안테나 (32 건, 15.4%)	Metasurface 안테나 (23 건, 11.1%)	Metasurface 안테나	19	9.1%
		Transparent Metasurface 안테나	2	1.0%
		변조용 Metasurface 안테나	1	0.5%
		홀로그래픽 Metasurface 안테나	1	0.5%
	지능형 Metasurface 안테나 (9 건, 4.3%)	지능형 Metasurface 안테나	9	4.3%
시스템 및 무선부품 (6 건, 3.0%)	Metamaterial 무선 부품 (3 건, 1.5%)	Metamaterial 무선 부품	3	1.5%
	Metasurface 기지국 (3 건, 1.5%)	Metasurface 기지국	3	1.5%
총합계			208	100.00%

특허정보 조사 분석: 정량 분석

▶ 대 분류 기술 기준 년도별 특허 정량 분석

- PCT, 미국, 유럽, 중국, 일본, 한국에 출원된 특허 수, 중복 출원 포함
- 관련 특허는 **2007년**에 나오기 시작했고, **4G가 상용화된 2011년에 정점을**, **초기 5G 상용화가 되었던 2019년에 두 번째 정점**
- Metamaterial 안테나 **81.7% (170건)**, Metasurface 안테나 **15.4% (32 건)**, 시스템 및 무선 부품 **2.9% (6 건)**
- Metamaterial 안테나는 **2011년까지 꾸준히 증가하다가 2012년부터 감소하였고, 2019년에 14건으로 다시 증가 추세**
- Metasurface 안테나는 **2015년에 처음 출원된 후 꾸준히 증가해서 2019년 13건으로 증가 추세**

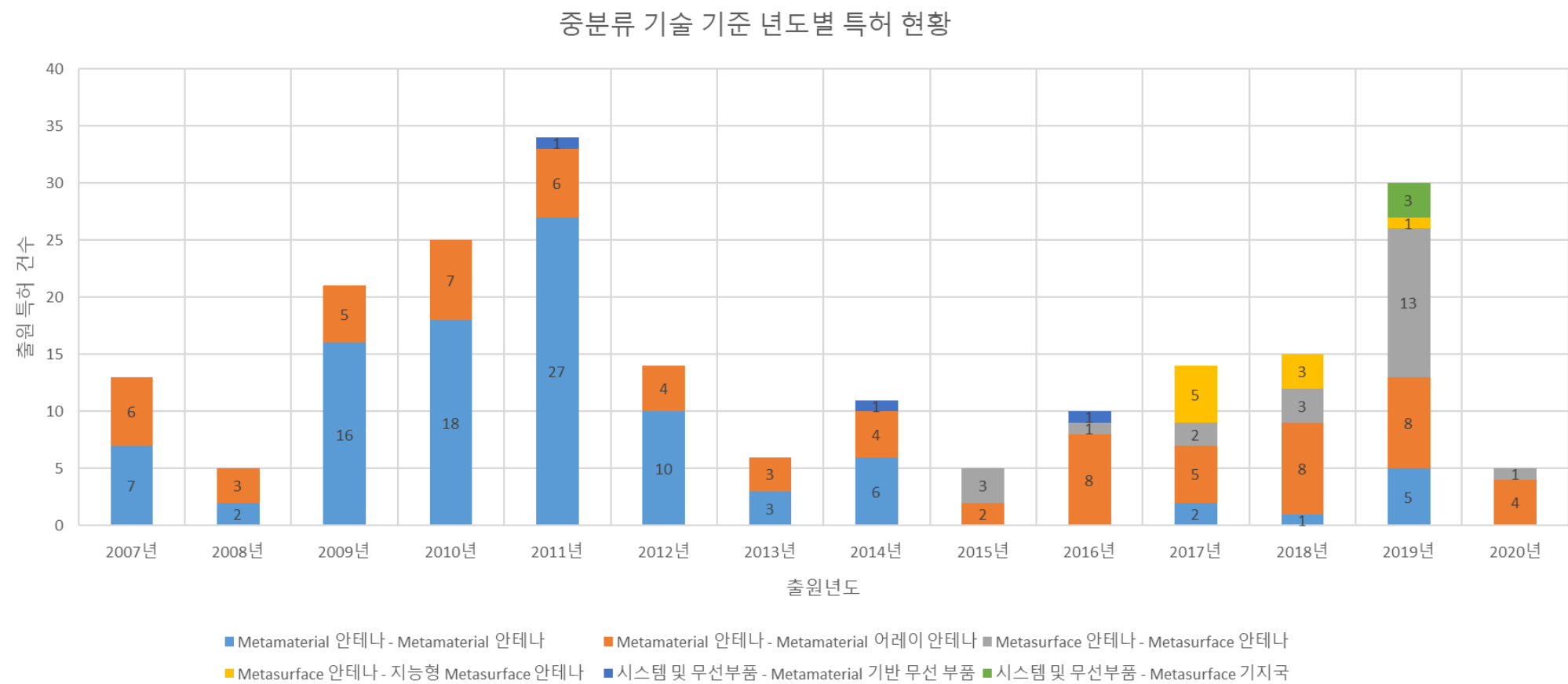
대분류 기술 기준 년도별 특허 현황



특허정보 조사 분석: 정량 분석

▶ 중분류 기술 기준 년도별 특허 정량 분석

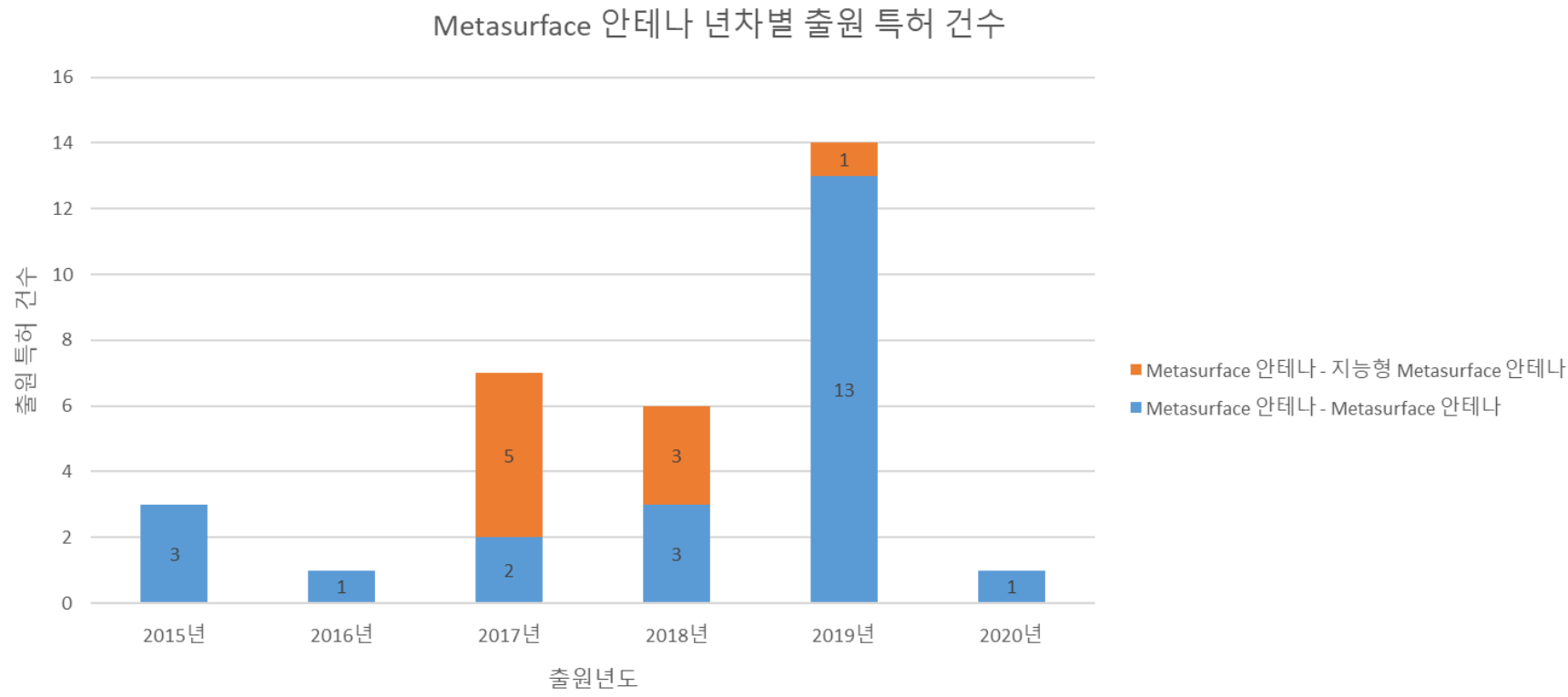
- 2007~2014년 동안에는 **Metamaterial** 안테나와 **Metamaterial** 어레이 안테나에 대한 특허만 있었으며, 2015년부터 **Metamaterial** 어레이 안테나 특허만 꾸준히 있었고,
- 2015년부터 신규로 **Metasurface** 안테나 특허가, 2017년에 **지능형 Metasurface** 안테나, 2019년에는 **Metasurface** 기지국 특허



특허정보 조사 분석: 정량 분석

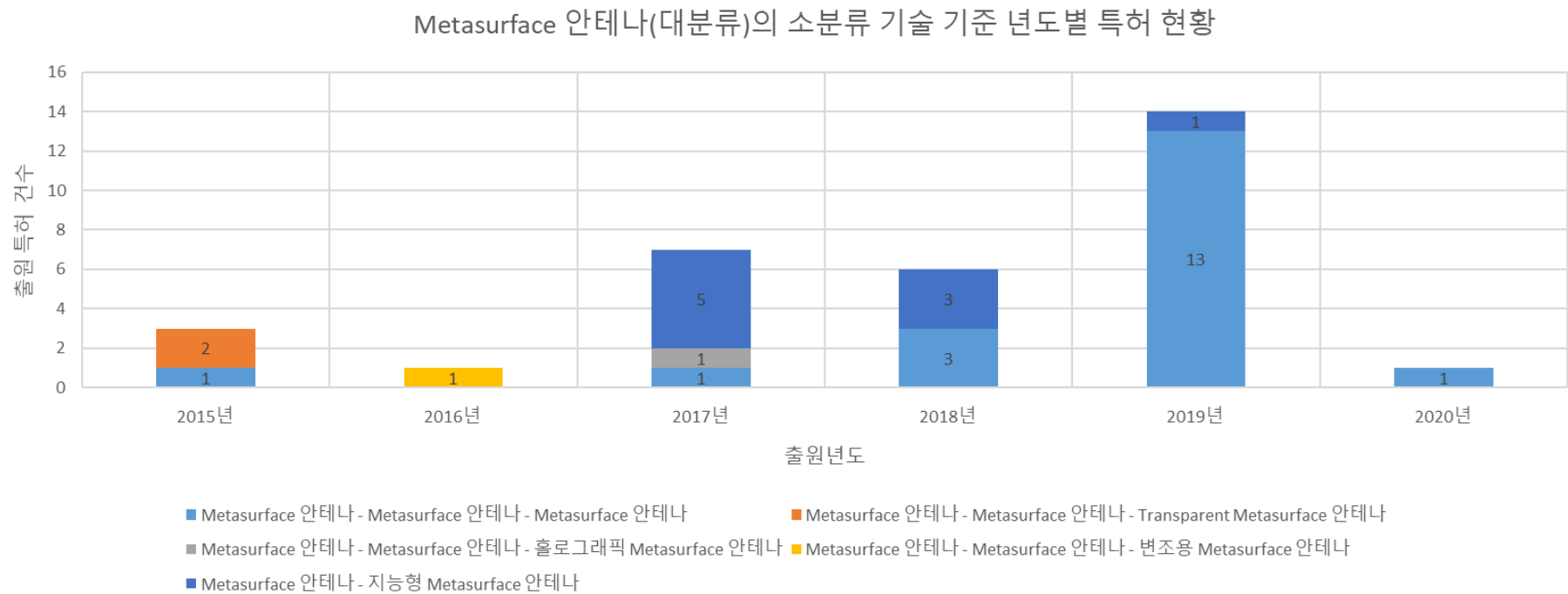
▶ 대분류 기술인 Metasurface 안테나 관련 년도별 출원 특허 정량 분석

- Metasurface 안테나내 중 분류기술 별 출원 특허 정량 분석 (PCT, 미국, 유럽, 중국, 일본, 한국에 출원된 특허 수, 중복 출원 포함)
 - Metasurface 안테나는 71.9% (23건), 지능형 Metasurface 안테나는 28.1% (9건)
 - 안테나의 기본 성능을 개선하는 Metasurface 안테나는 2015년 처음 출원된 후 2019년에 13건으로 증가
 - 지능형 Metasurface 안테나는 2017년 처음 출원 됨



특허정보 조사 분석: 정량 분석

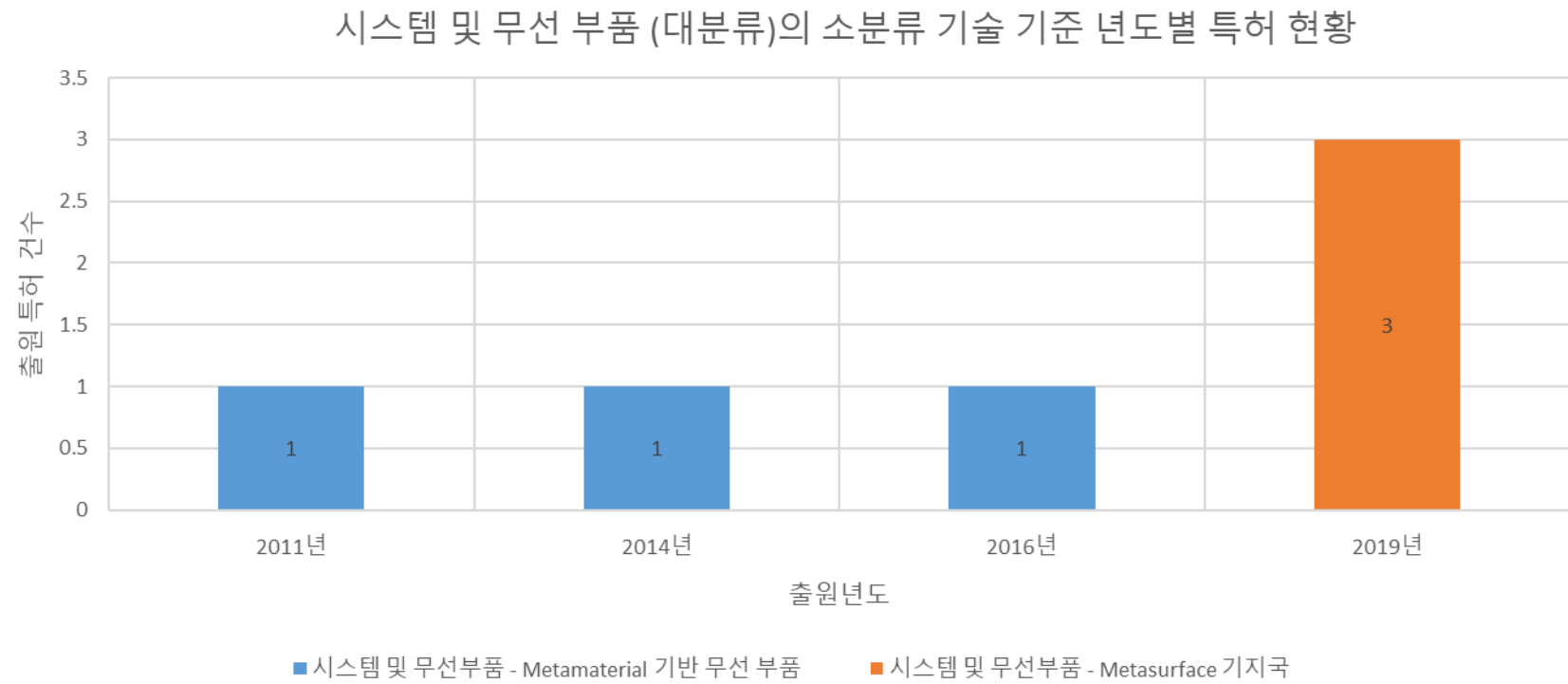
- Metasurface 안테나 (대분류)내 소 분류 기술관련 특허 정량 분석 (PCT, 미국, 유럽, 중국, 일본, 한국에 출원된 특허 수, 중복 출원 포함)
 - 안테나의 기본 성능을 개선하는 Metasurface 안테나는 2015년 처음 출원된 후 2019년에 13건으로 증가
 - Metasurface 안테나를 변조, Transparent 용도로 사용하거나, 홀로그래픽 기술을 적용한 특허 2015-2017 동안 1-2개 출원 됨
 - 지능형 Metasurface 안테나는 2017년을 시작으로 출원되기 시작해서 미미한 상황



특허정보 조사 분석: 정량 분석

▶ 대분류 기술인 시스템 및 무선 부품 관련 년도별 출원 특허 정량 분석

- 총 6건으로 미미함
- Metasurface기반 무선 부품은 2011/2014/1016 년 각 1건
- 지능형 Metasurface 기지국은 2019년에 3건



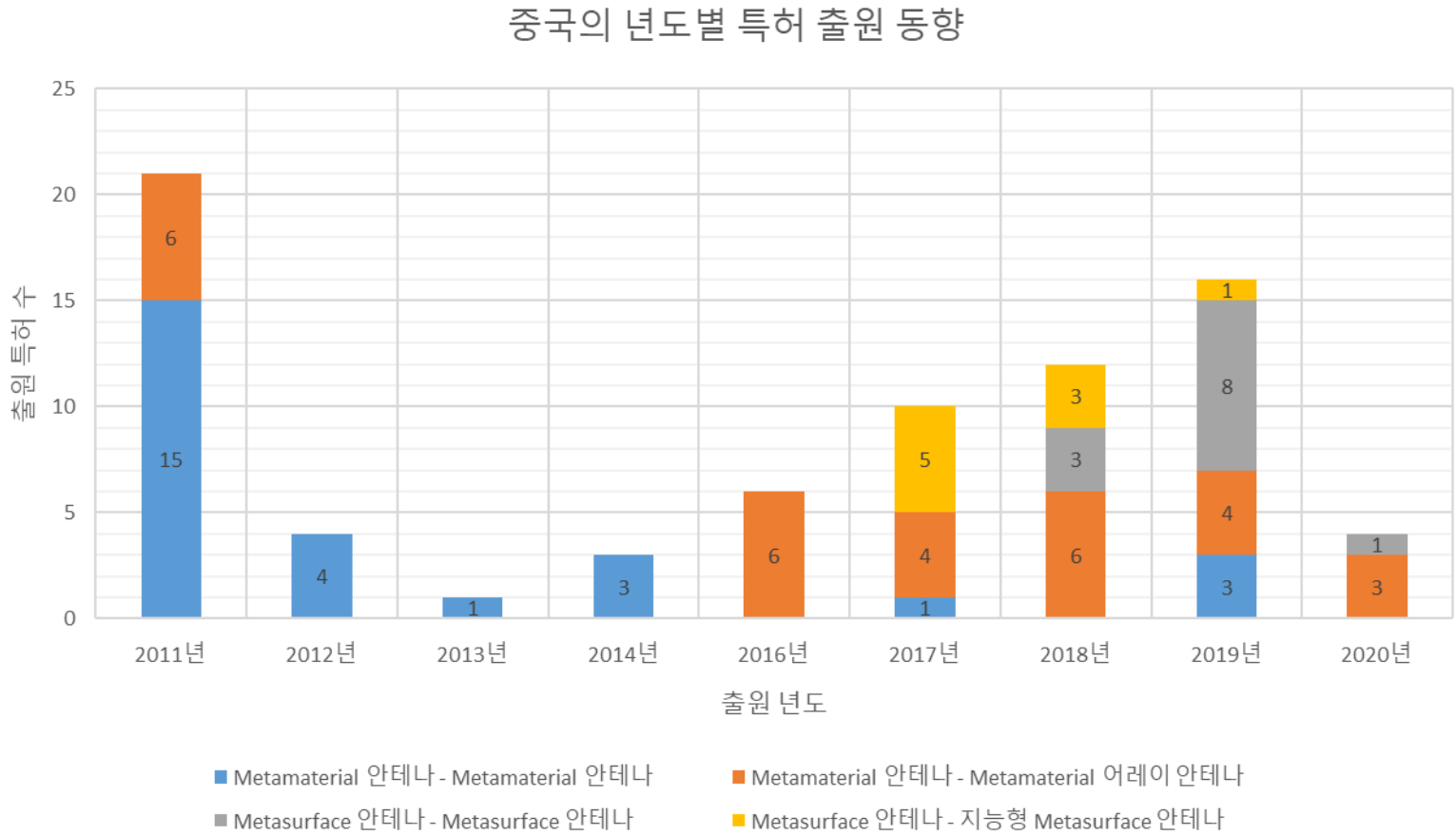
특허정보 조사 분석: 정량 분석

▶출원인 국적별 특허 정량분석 (중분류 기준, PCT/유럽/미국/중국/한국/일본 DB)

기술 분류	중국	한국	미국	스위스	인도	일본	TH	이탈리아	스웨덴	캐나다	대만	MA	총합계
Metamaterial 안테나	56	40	42	17	4	3	2	2	1	1	1	1	170
Metamaterial 안테나	27	33	16	12	4	1	2				1	1	97
Metamaterial 안테나	24	24	12	4		1	2				1	1	69
단말기 Metamaterial 안테나	3	9	4	8	4								28
Metamaterial 어레이 안테나	29	7	26	5		2		2	1	1			73
Metamaterial Lens 안테나	10		4										14
Metamaterial Liquid Crystal 어레이 안테나	4												4
Metamaterial 어레이/MIMO 안테나	7	7	17	4		2		2	1	1			41
기계학습기반 Metamaterial 어레이 안테나	1		3										4
단말기 Metamaterial 어레이 안테나	1			1									2
반사 Metamaterial 어레이 안테나	2		2										4
변조용 Metamaterial 어레이 안테나	3												3
홀로그래픽 Metamaterial 어레이 안테나	1												1
Metasurface 안테나	21	7	4										32
Metasurface 안테나	12	7	4										23
Metasurface 안테나	12	6	1										19
Transparent Metasurface 안테나			2										2
변조용 Metasurface 안테나		1											1
홀로그래픽 Metasurface 안테나			1										1
지능형 Metasurface 안테나	9												9
지능형 Metasurface 안테나	9												9
시스템 및 무선부품	3	1	2										6
Metamaterial 기반 무선 부품		1	2										3
Metamaterial 기반 무선 부품		1	2										3
Metasurface 기지국	3												3
지능형 Metasurface 기지국	3												3
총합계	80	48	48	17	4	3	2	2	1	1	1	1	208

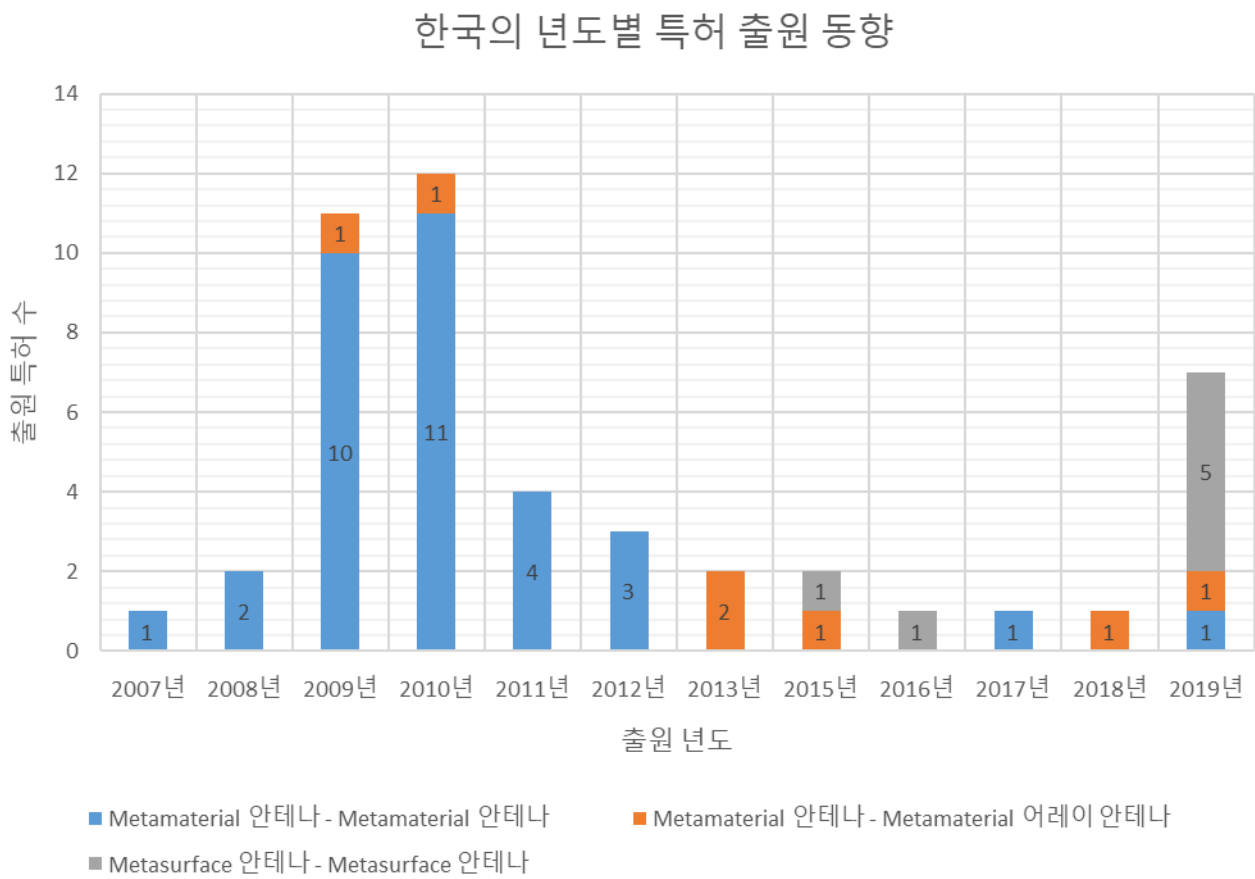
특허정보 조사 분석: 정량 분석

- 중국 국적의 출원인 특허 출원 동향
 - 2011년부터 Metamaterial 안테나 → 2016년부터 Metamaterial 어레이 안테나 / Metasurface 안테나 / 지능형 Metasurface 안테나



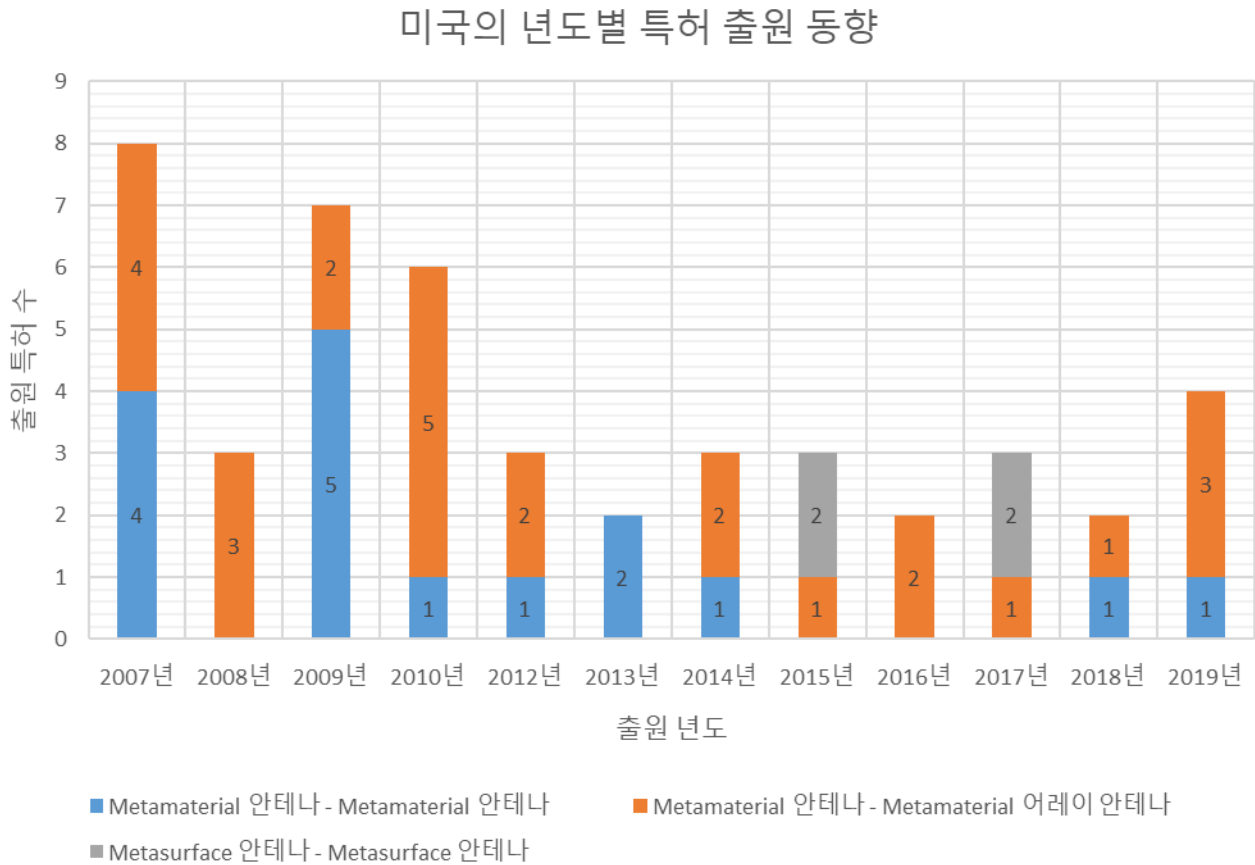
특허정보 조사 분석: 정량 분석

- 한국 국적의 출원인 특허 출원 동향
 - 2007년부터 Metamaterial 안테나 → 2013년부터 Metamaterial 어레이 안테나 / Metasurface 안테나



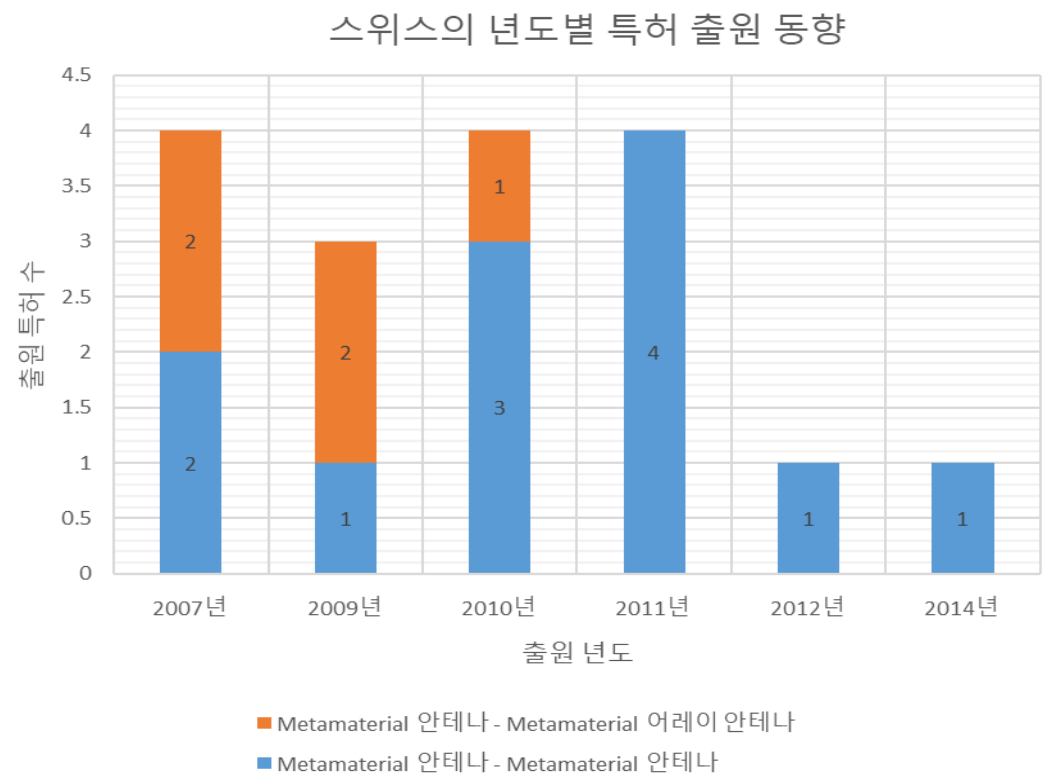
특허정보 조사 분석: 정량 분석

- 미국 국적의 출원인 특허 출원 동향
 - 2007년부터 Metamaterial 안테나 / Metamaterial 어레이 안테나 출원 시작으로 점차 감소
 - 2015/2017년 Metasurface 안테나



특허정보 조사 분석: 정량 분석

- 스위스 국적의 출원인 특허 출원 동향
 - 2007년부터 Metamaterial 안테나 / Metamaterial 어레이 안테나 → 2011년부터 Metamaterial 안테나



특허정보 조사 분석: 정량 분석

- 미국에 출원된 특허 중 주요 출원인 국적별 특허 정량분석 (중분류 기준)
 - (미국, 27) **Metamaterial** 어레이 안테나 (11), Metamaterial 안테나 (6), 기계학습 Metamaterial 어레이 안테나 (3), Metasurface 안테나 (3),
 - (중국, 5) Metamaterial Liquid Crystal 어레이 안테나 (2), Metamaterial Lens 안테나 (1), Metamaterial MIMO 안테나 (1), Metasurface Reflector (1)
 - (한국, 5) Metamaterial 어레이 안테나 (3), Metamaterial 안테나 (2)
 - (시사점)
 - Metamaterial 어레이 안테나는 미국이 주도,
 - Liquid Crystal 관련 특허는 중국이 주도
-
- PCT에 출원된 특허 중 주요 출원인 국적별 특허 정량분석 (중분류 기준)
 - (미국,11) Metamaterial 안테나 (5), Metamaterial 어레이 안테나 (4), Metasurface 안테나 (1)
 - (중국, 10) Metamaterial 어레이 안테나 (3), Metamaterial 안테나 (2), Metamaterial Liquid Crystal 어레이 안테나 (1), Metasurface MIMO 안테나 (1), Metasurface Reflector (1)
 - (한국, 11) **Metamaterial** 안테나 (11)
 - (시사점)

기술 분류 (대/중)	스위스	중국	한국	미국	합계
Metamaterial 안테나	12	4	5	23	44
Metamaterial Lens 안테나		1		2	3
Metamaterial Liquid Crystal 안테나		2			2
Metamaterial MIMO 안테나		1		1	2
Metamaterial 안테나	9		2	6	17
Metamaterial 어레이 안테나	3		3	11	17
기계학습 Metamaterial 어레이 안테나				3	3
Metasurface 안테나		1		3	4
Metasurface reflector		1			1
Metasurface 안테나				2	2
Programmable Metasurface 안테나				1	1
시스템 및 무선부품				1	1
Metamaterial diplexers, combiners and dividers				1	1
총합계	12	5	5	27	49

기술 분류 (대/중)	중국	한국	미국	합계
Metamaterial 안테나	8	11	10	29
Metamaterial Lens 안테나	1		1	2
Metamaterial Liquid Crystal 안테나	1			1
Metamaterial MIMO 안테나	1			1
Metamaterial 안테나	2	11	5	18
Metamaterial 어레이 안테나	3		4	7
Metasurface 안테나	2		1	3
Metasurface MIMO 안테나	1			1
Metasurface reflector	1			1
Metasurface 안테나			1	1
총합계	10	11	11	32

특허정보 조사 분석: 정량 분석

- 한국에 출원된 특허 중 주요 출원인 국적별 특허 정량분석 (중분류 기준)
 - (미국,4) Metamaterial 안테나 (2), Metamaterial 어레이 안테나 (2)
 - (한국, 31) Metamaterial 어레이 안테나 (19) > Metasurface 안테나 (6) > Metamaterial MIMO 안테나 (3)
- 중국에 출원된 특허 중 주요 출원인 국적별 특허 정량분석 (중분류 기준)
 - (중국, 61) Metamaterial 안테나 (25) > Metasurface 안테나 (11) > Metamaterial Lens 안테나 (3), Programmable Metasurface 안테나 (3)
 - (스위스, 3) Metamaterial 안테나 (2) > Metamaterial 어레이 안테나 (1)

기술 분류 (대/중)	한국	미국	합계
Metamaterial 안테나	23	4	27
Metamaterial MIMO 안테나	3		3
Metamaterial 안테나	19	2	21
Metamaterial 어레이 안테나	1	2	3
Metasurface 안테나	7		7
Metasurface 안테나	6		6
Programmable Metasurface 안테나	1		1
시스템 및 무선부품	1		1
Metamaterial 다중 안테나 급전 장치	1		1
총합계	31	4	35

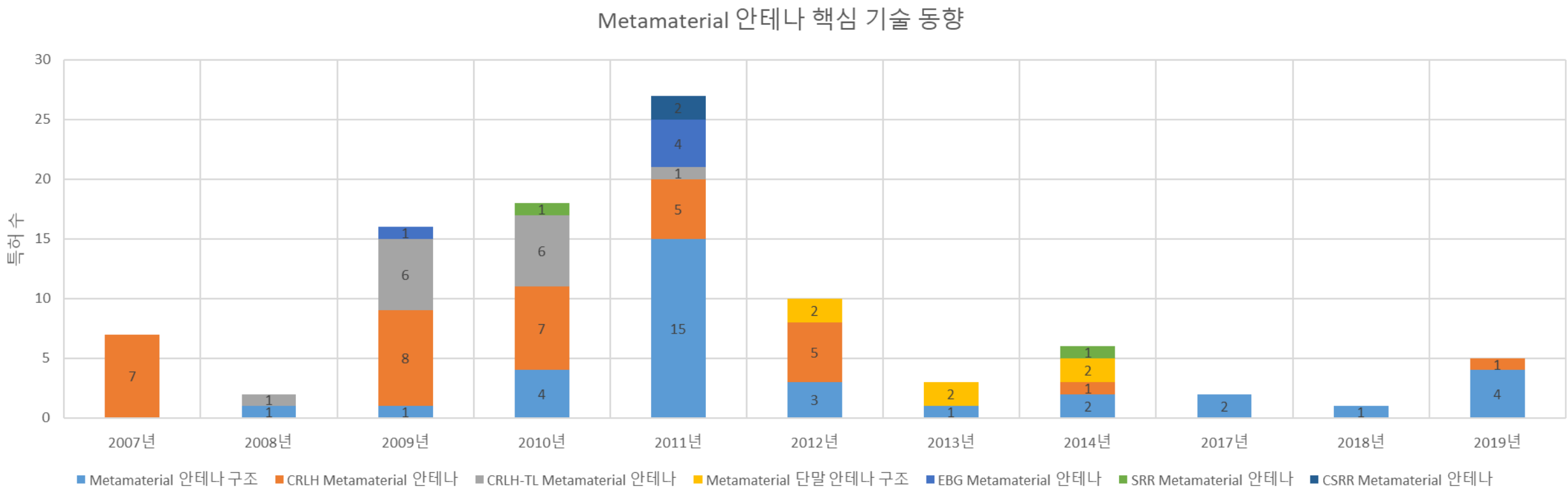
기술 분류 (대/중)	스위스	중국	한국	미국	합계
Metamaterial 안테나	3	41	1	1	46
Metamaterial Lens 안테나		7			7
Metamaterial MIMO 안테나		3			3
Metamaterial 안테나	2	25	1	1	29
Metamaterial 어레이 안테나	1	5			6
기계학습 Metamaterial 어레이 안테나		1			1
Metasurface 안테나		17			17
Metasurface MIMO 안테나		2			2
Metasurface reflector		1			1
Metasurface 안테나		11			11
Programmable Metasurface 안테나		3			3
시스템 및 무선부품		3			3
Programmable Metasurface 무선 Relay		1			1
지능형 Metasurface 기지국		2			2
총합계	3	61	1	1	66

특허정보 조사 분석: 정성 분석

▶ 중분류 기술 기준별로 특허의 핵심 기술에 대한 연도별 동향 분석

● Metamaterial 안테나

- 총 97 건 중 **CRLH**와 **CRLH-TL** 기술이 **48** 건, 단말 포함 Metamaterial 안테나 실현 다양한 기술이 40 건, 그리고 EBG 기술이 5 건
- **2011**년까지는 **CRLH**와 **CRLH TL** 기술이 중심이었으나, **2011**년부터는 다양한 **Metamaterial** 안테나 실현 기술이 등장

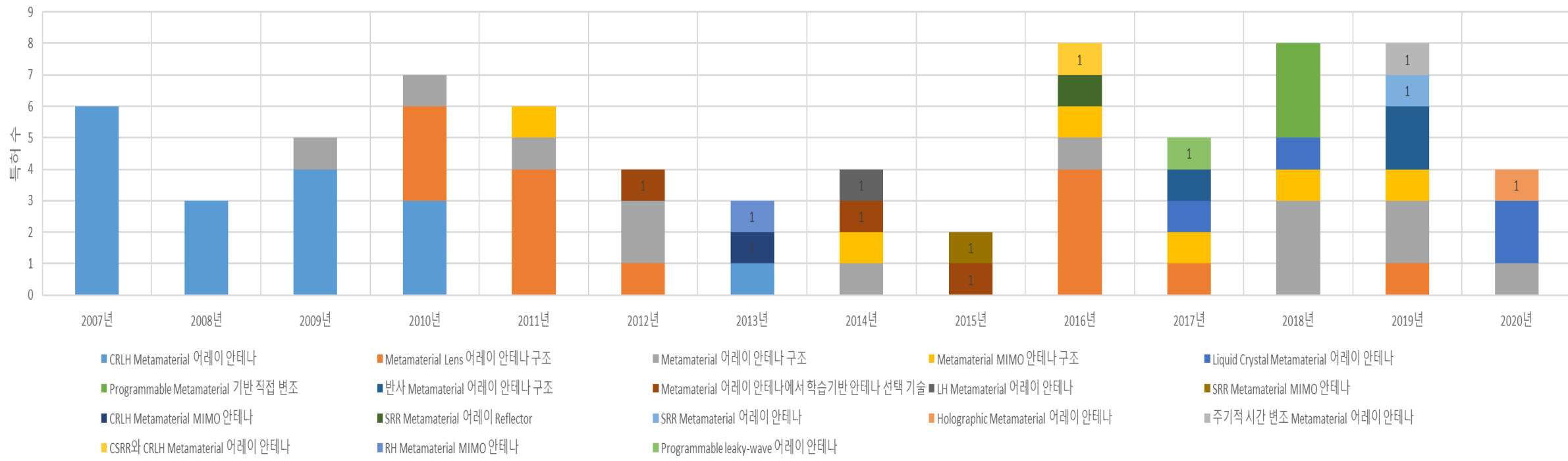


특허정보 조사 분석: 정성 분석

● Metamaterial 어레이 안테나

- 총 73 건 중 **CRLH** 어레이 안테나 기술이 **17** 건, **Lens** 어레이 안테나 구조가 **14** 건, 어레이 안테나 구조가 **13** 건, MIMO 안테나 구조가 6 건 순
- 2010년까지는 CRLH 어레이 안테나 기술이 주를 이루었으나, **2009**년부터는 다양한 어레이 안테나 구조 특허가, **2010**년부터 **Lens** 어레이 안테나 구조 특허가, **2011**년부터는 **MIMO** 안테나 구조 특허가 출원되기 시작
- 2012년부터는 재구성, 반사, **Liquid Crystal**, 직접 변조, 기계학습 적용, **LH**, **SRR** 등 다양한 특허가 출원

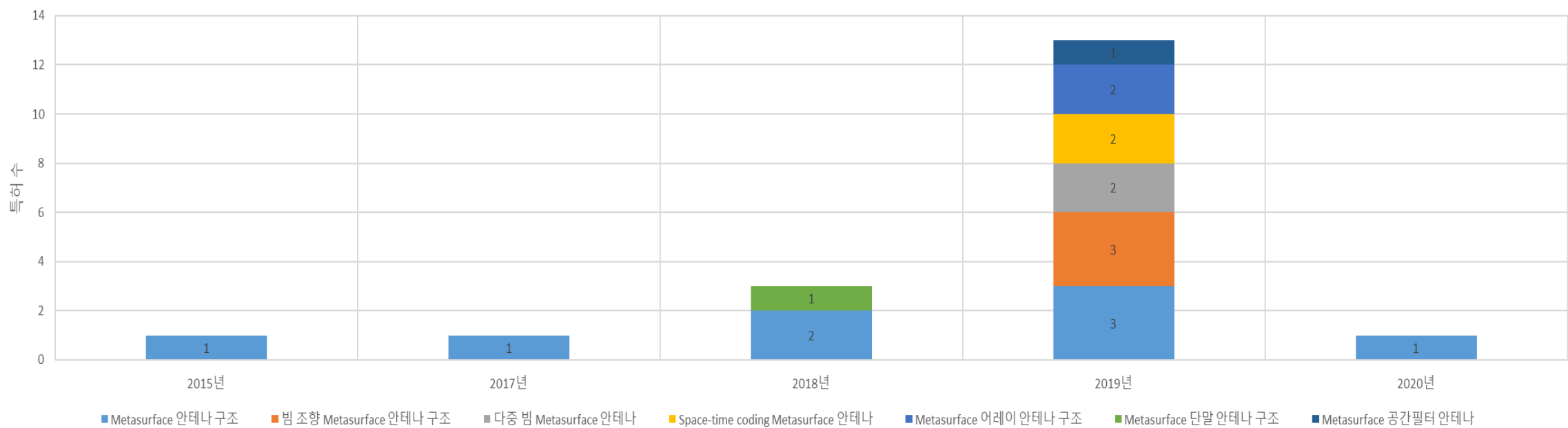
Metamaterial 어레이 안테나 핵심 기술 동향



특허정보 조사 분석: 정성 분석

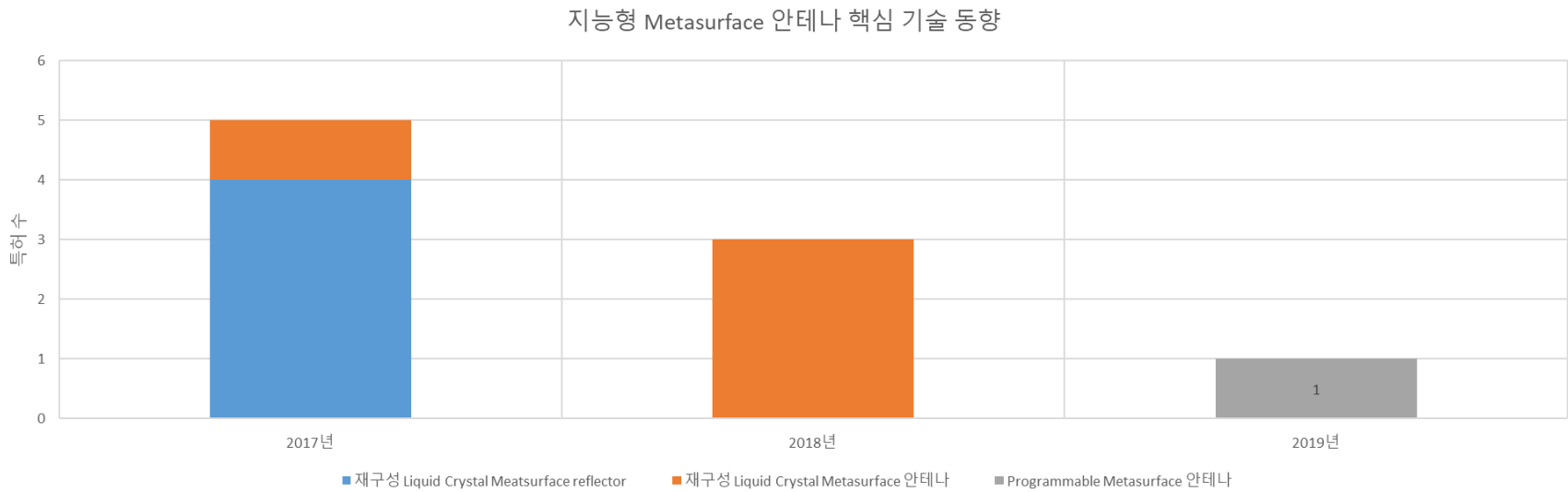
- Metasurface 안테나
 - 총 19 건 특허 중 다양한 **Metasurface** 안테나 구조가 8 건, 빔 조향 **Metasurface** 안테나 구조가 3 건, 다중 빔/Space-time coding Metasurface 안테나가 각각 2 건씩, Metasurface 어레이 안테나 구조가 2건,
 - Metasurface 안테나 구조 특허는 2015년 이후 계속 있으며, 2019년에 다중 빔/Space-time coding Metasurface 안테나와 Metasurface 어레이 안테나가 2 건이상씩 출원

Metasurface 안테나 핵심 기술 동향



특허정보 조사 분석: 정성 분석

- 지능형 Metasurface 안테나
 - 총 9 건 중 8 건이 **Liquid Crystal Metasurface reflector/안테나**로, 전체적으로 매우 초기 단계



특허정보 조사 분석: 정성 분석

▶ 기술 분류별 핵심 특허 기술 분석

대분류	중분류	소분류	주요 기술
Metamaterial 안테나	Metamaterial Lens 안테나	다중 빔 Metamaterial Lens 어레이 안테나 (4)	Time-delay unit셀 Metamaterial Lens 어레이 안테나
	Metamaterial Liquid Crystal 안테나	다중 빔 재구성 Metamaterial Liquid Crystal 어레이 안테나	개별 제어가 가능한 Liquid Crystal Tunable Metamaterial Lens기반 2차원 phase variable Lens 그룹으로 구성된 위상 어레이 구조
	Metamaterial MIMO 안테나	광대역 Metamaterial MIMO 안테나	Metamaterial MIMO 안테나 구조
		소형 Metamaterial MIMO 안테나	Magnetic permeability enhanced Metamaterial MIMO 안테나
	Metamaterial 안테나	광대역 Metamaterial 안테나	CRLH Metamaterial 안테나 다층 구조 단위 셀로 구성된 C R L H - T L 주기 구조 Metamaterial 안테나 CSRR Metamaterial 패치 안테나
		빔 포밍 Metamaterial 안테나	Metamaterial 안테나 구조
	Metamaterial 어레이 안테나	Metamaterial 어레이 안테나	CRLH Metamaterial 어레이 안테나 Flat panel Metamaterial 안테나 Flat panel Metamaterial 어레이 안테나 CRLH Metamaterial과 분산 증폭기가 결합한 Metamaterial 어레이 안테나 기지국 시스템 Metamaterial 패치 어레이 안테나
		광대역 Metamaterial 어레이 안테나	CRLH-TL Metamaterial 어레이 안테나
		무선채널 변조 Metamaterial 어레이 안테나	Programmable Metamaterial 채널 직접 변조
		반사 Metamaterial 어레이 안테나	신호 반사 방향을 제어하는 제어 모듈을 갖는 Metamaterial 어레이 안테나
		빔 스위칭 Metamaterial 어레이 안테나	CRLH Metamaterial 어레이 안테나
		빔 스캐닝 Metamaterial 어레이 안테나	CSRR와 CRLH을 적용한 Metamaterial leaky-wave 어레이 안테나 Metamaterial 어레이 안테나 구조
		Heterodyning Metamaterial 어레이 안테나	Passive Heterodyning Metamaterial 어레이 안테나
		Holographic Metamaterial 어레이 안테나	Digital coding하는 Holographic Metamaterial 어레이 안테나
	기계학습 Metamaterial 어레이 안테나	학습기반 Metamaterial 어레이 안테나 선택 기술	Metamaterial Reconfigurable Leaky Wave 어레이 안테나에서 온라인 학습기반 안테나 선택 기술
		지능형 Metamaterial 어레이 안테나	Programmable leaky-wave 어레이 안테나

특허정보 조사 분석: 정성 분석

▶ 기술 분류별 출원 특허 목적 또는 기능 또는 효과 분석

대분류	중분류	소분류	주요 기술
Metasurface 안테나	Metasurface 안테나	다중 빔 Metasurface 안테나	안테나 선택과 위상 차이 조절을 하는 Metasurface MIMO 안테나 복수의 유전체를 이용한 다중 빔 Metasurface안테나
		빔 스티어링 Metasurface 안테나	비선형 MetaSurface 안테나
		빔 포밍 Metasurface 안테나	Metasurface 공간필터 안테나
	Metasurface MIMO 안테나	다중 사용자 Metasurface MIMO 안테나	Space-time coding Metasurface 다중 사용자
		다중 빔 재구성 Liquid Crystal Metasurface MIMO 안테나	개별 제어가 가능한 Liquid Crystal Tunable Metamaterial Lens기반 2차원 phase variable Lens 그룹으로 구성된 위상 어레이 구조
	Metasurface reflector	재구성 Liquid Crystal Metasurface reflector	반사된 RF 신호의 빔 스티어링
시스템 및 무선 부품	Programmable Metasurface 안테나	재구성 Metasurface 안테나	전자기파를 제어하는 FPMS Metasurface 안테나 Substrate integrated waveguide Programmable Metasurface 안테나
	지능형 Metasurface 기지국	기계학습 Metasurface 기지국	분산 기지국에서 지능형 처리를 위한 Metasurface 시스템
	Programmable Metasurface 무선 Relay	Programmable Metasurface 무선 Relay	Programmable Metasurface 3D 빔포밍을 위한 무선 Relay 시스템 프레임 구조

특허정보 조사 분석: 결론

- ▶ 안테나는 기본적으로 통신 커버리지 확보의 한 요소로 여겨졌으나, 다양한 이동통신 주파수 대역을 수용하기 위해 안테나의 이득-점유 대역폭-크기 간의 Trilemma 문제 해결을 위해 2000년대 중반 이후 Metamaterial 안테나 연구 개발 시작
- ▶ 한편, 4G 이후 다중 어레이 시스템에서 적응적 재구성 기능이 필요해지고, Metamaterial 안테나 실현 수단이 안테나의 기본 구조 변경에서 다이오드, Liquid Crystal 등 가변 가능한 소자를 활용한 Metamaterial 어레이 안테나 연구개발 진행.
- ▶ 최근에는 Metamaterial 안테나를 방사 요소로 만이 아니라 랜덤하게 변동하는 무선 채널에 효과적으로 대처하기 위해 반사/투과/변조 등 다양한 용도로 사용하기 위해 Metasurface 안테나에 기계학습 기술을 적용한 RIS 연구.
- ▶ 그런데, 본 논문에서 조사 분석한 관련 특허 동향에 따르면.
 - 우선은 Metamaterial 안테나, Metamaterial 안테나에 대한 연구개발이 대부분이었고,
 - Metasurface 안테나 기술에 대한 연구는 초기 단계임을 확인.
 - 초기 단계인 Metasurface 안테나의 지능화에 대한 연구가 매우 미미하므로 B5G 와 6G에서 특허 경쟁력 확보를 위해 RIS에 대한 연구개발 투자가 시급하다.

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Open Research Issues

► EM-based circuital models

State-of-the-art	Issues, Problems, Limitations	Directions
<p>The homogenized and macroscopic model-based approach (either based on surface susceptibility functions or surface impedances) is a powerful method for analyzing and optimizing RISs.</p> <p>It constitutes a suitable interface between the physics phenomena underlying the operation of RISs and the level of abstraction that is needed for obtaining adequately accurate but sufficiently tractable models for application to wireless communications.</p>	<p>This approach hides some aspects related to the practical realization of RISs, which may be convenient to preserve in the analytical formulation.</p>	<p>For analyzing and optimizing wireless networks, it may be appropriate to start from simple models for the unit cell of metasurfaces and to obtain equivalent EM-based circuital models for metasurface structures, which explicitly account for the mutual coupling among the unit cells as a function of their size, inter-distance, and spatial arrangements.</p> <p>→ This will allow us to better understand the potential benefits and limitations of sub-wavelength metasurface structures, and to better quantify the potential gains for wireless applications.</p>

Open Research Issues

► Path-loss and Channel Modeling

State-of-the-art	Issues, Problems, Limitations	Directions
<p>Recently, a few initial research works have attempted to shed light on modeling the path-loss of RISs.</p> <ul style="list-style-type: none">In [13], the authors perform a measurement campaign in an anechoic chamber and show that <u>the power reflected from an RIS follows a scaling law that depends on many parameters</u>, including the size of the RIS, the mutual distances between the transmitter/receiver and the RIS (i.e., near-field vs. far-field conditions), and whether the RIS is used for beamforming or broadcasting applications.In [76], the authors employ antenna theory to compute the electric field in the near-field and far-field of a finite-size RIS, and prove that <u>an RIS is capable of acting as an anomalous mirror in the near-field of the array</u>. The results are obtained numerically and no explicit analytical formulation of the received power as a function of the distance is given. Similar findings are reported in [77].In [78], the authors study, through experimental measurements, <u>the power scattered from passive reflectors that operate in the millimeter-wave frequency band</u>. Also, the authors compare the obtained results against ray tracing simulations. By optimizing the area of the surface that is illuminated, it is shown that a finite-size passive reflector can act as an anomalous mirror.In [79], the authors study <u>the path-loss of RISs in the far-field regime by leveraging antenna theory</u>. The obtained results are in agreement with those reported in [76] and [77] under the assumption of far-field propagation.In [42], the authors use <u>the scalar theory of diffraction and the Huygens-Fresnel principle in order to model the path-loss in both the near-field and far-field of RISs, which are modeled as homogenized sheets of electromagnetic material with negligible thickness</u>. By using the stationary phase method, the authors unveil the regimes under which the path-loss depends on the sum and the product of the distances between the RIS and the transmitter, and the RIS and the receiver. The proposed analytical approach is shown to be sufficiently general for application to uniform reflecting surfaces, anomalous reflectors, and focusing reflecting lenses.	<p>A major research issue for analyzing the ultimate performance limits, optimizing the operation, and assessing the advantages and limitations of RIS-empowered SREs is <u>the development of simple but sufficiently accurate models for the power received at a given location in space when a transmitter emits radio waves that illuminate an RIS</u>.</p>	<p>In order to evaluate the performance limits of RISs in wireless networks, we need realistic models for the propagation of the signals scattered by metasurfaces.</p> <p>It is necessary to abandon the comfortable assumption of far-field propagation, since several promising applications and potential advantages of RISs may emerge in the radiative near-field regime. It is necessary to relay upon physics-based models for the propagation of EM fields in proximity of metasurfaces and to account for their circuital models in the problem formulation.</p> <p>Besides the development of accurate path-loss models for link budget analysis, it is necessary to <u>develop fading models for sub-wavelength structures</u>, both at the microscopic level, which account for individual unit cells, and at the macroscopic level, which may be more easily integrated into communication-theoretic frameworks.</p>

Open Research Issues

► Fundamental Performance Limits

State-of-the-art	Issues, Problems, Limitations	Directions
<p>Recent results have pointed out, in a simple point-to-point communication setup, that the channel capacity is achieved by performing joint encoding at the transmitter and RIS, whereas typical criteria that rely on maximizing the power of the received signal are sub-optimal.</p> <p>However, these findings are obtained by considering simple models for the metasurface structure, which are in agreement with conventional assumptions in communication and information theory.</p> <p>RISs have been under study for unveiling their fundamental performance limits and the impact of the imperfect knowledge of various systems parameters on their achievable performance.</p> <p>In this context, several exact, approximate, and asymptotic analytical frameworks have been developed in order to quantify the advantages and limitations of RISs in different network scenarios.</p>	<p>RISs can be employed for different purposes, which include beamsteering, beamforming, focusing, modulation, and joint modulation and encoding with the transmitter.</p> <p>Depending on the specific application and wave transformation applied, the ultimate performance limits are not known yet.</p>	<p>The ultimate performance limits of RISs, how to best configure RISs to achieve them, and the actual gains with respect to other well established technologies are not known yet.</p>

► Robust optimization and resource allocation

State-of-the-art	Issues, Problems, Limitations	Directions
	<p>Physics-based models for simple metasurfaces, e.g., perfect anomalous reflectors, are more complex than the typical models that communication theorists employ in formulating resource allocation problems.</p> <p>As an example, the amplitude and phase responses of a metasurface operating as a perfect anomalous reflector are not independent of each other, and the resulting metasurface structure is locally non-passive.</p>	<p>It is necessary to integrate physics-based models for metasurface structures into resource allocation problems, and to explicitly account for the impact of the sub-wavelength structure of RISs and the associated design constraints and shaping capabilities of the radio waves.</p>

Open Research Issues

► Constrained system design and optimization

State-of-the-art	Issues, Problems, Limitations	Directions
	<p>One of the potential novelties of RISs is the possibility of manipulating the radio waves impinging upon them without the need of relying on on-board power amplifiers and signal processing units. Some advantages of these assumptions lie in the opportunity of reducing the EM field exposure of human beings and in making the metasurfaces easier to recycle. → These assumptions introduce constraints on the operation of RISs when they are deployed in wireless networks.</p> <p>Usually, the restrictions on performing signal processing operations on the metasurfaces have an impact on the overhead that is associated with gathering the necessary environmental information for optimizing and configuring RISs.</p>	<p>The fundamental trade-off between the complexity and power consumption of RISs, as well as the associated overhead needs to be carefully investigated and assessed.</p>

► Large-scale networks: Deployment, analysis, and optimization

State-of-the-art	Issues, Problems, Limitations	Directions
<p>RIS-empowered SREs have several potential applications, which encompass indoor and outdoor environments.</p> <p>The vast majority of research activities conducted so far have considered the analysis of optimization of “small-size” networks, usually networks that are made of a single RIS.</p> <p>In addition, the analysis of these simple scenarios is based on modeling assumptions that may not necessarily be sufficiency realistic for the assessment of sub-wavelength metasurfaces.</p>	<p>It instrumental to quantify the performance limits of SREs in large-scale deployments.</p> <p>For example, a relevant question may be to identify the density of RISs to be deployed for increasing the coverage probability or the energy efficiency in a large industrial factory or even in the downtown of a city. This is an almost unexplored research problem to be tackled.</p>	

Open Research Issues

► EM-based communications: “Layer-0” networking

- RISs may open the possibility of designing wireless networks in which the entire protocol stack for communication is realized through an appropriate shaping and manipulation of the radio waves at the EM level.
 - This does not encompass only physical layer functionalities but the medium access control layer and the routing layer as well.

State-of-the-art	Issues, Problems, Limitations	Directions
<p>In scenarios with a high density of mobile terminals and devices, RISs may be employed to create a large number of orthogonal wireless channels that may be employed for achieving high spatial capacities through EM-based medium access control protocols with reduced overhead and contention time, as well as for enabling spatial multiplexing gains in rank-deficient wireless environments.</p> <p>RIS-empowered SREs may be viewed as an opportunity to realize EM-based routing protocols (see, e.g., Fig. 34), according to which the radio waves are routed from the transmitter to the receiver via controlled reflections and refractions at low latencies, low transmission delays/jitters, and high reliability, since all operations are realized directly at the EM level.</p>	<p>Research on the potential uses, advantages, and limitations of capitalizing on RISs for the design of communication protocols beyond the physical layer is almost unexplored to date but deserves major attention and research efforts.</p>	

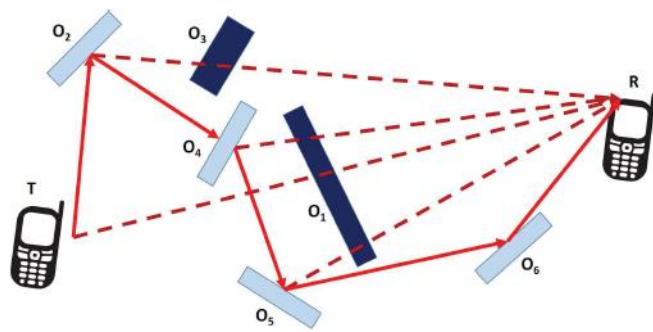


Fig. 34. Electromagnetic-based routing in smart radio environments (reproduced from [47]).

Open Research Issues

- Ray tracing and system-level simulators
 - The deployment phase of new technologies is usually preceded by extensive system-level simulation studies and field test trials. In this context, the use of ray tracing and system-level simulators plays a crucial role for overcoming the limitations of simplified analytical studies, and for taking into account realistic spatial topologies, e.g., three-dimensional maps for territories, cities, streets, buildings, and floor plants of apartments, offices, etc.

State-of-the-art	Issues, Problems, Limitations	Directions
	<p>Current tools that are employed to this end are not suitable for application to RIS-empowered SREs because the wave transformations and the scattering models of metasurfaces are not integrated into them.</p> <p>The so-called generalized laws of reflection and refraction that can be viewed as approximations of the response of metasurfaces to impinging radio waves according to the assumptions of geometric optics are not available in commercial ray tracing tools and system-level simulators.</p>	

Open Research Issues

► Beyond far-field communications

State-of-the-art	Issues, Problems, Limitations	Directions
<p>Most research works conducted in the recent present on RIS-empowered SREs rely upon far-field assumptions. RISs may be made of geometrically large surfaces of the order of a few square meters. This implies that RISs may operate in the near-field regime in relevant application scenarios, e.g., in indoor environments.</p> <p>The use of geometrically large RISs opens the possibility of building new wireless networks that operate in the near-field regime, which is not a conventional design assumption in wireless communications.</p>	<p>Research on the fundamental performance limits, design constraints, and potential applications and benefits of near-field communications in RIS-empowered SREs has not received significant attention so far.</p>	<p>In light of the potential applications that may be unlocked, e.g., highly focusing capabilities, the near-field regime is worthed of further attention from the research community.</p>

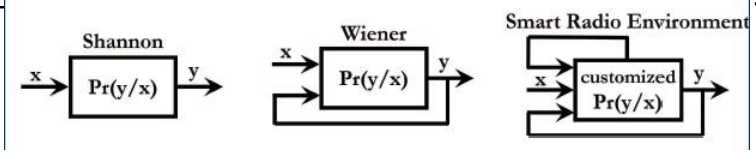
► Beyond communications

State-of-the-art	Issues, Problems, Limitations	Directions
<p>Most research works conducted in the recent present on RIS-empowered SREs are focused on applications that are related to communications.</p> <p>RISs offer opportunity for research that go beyond communications.</p> <p>The high focusing capability of electrically large RISs offers the opportunity of using them for high-precision radio localization and mapping (i.e., the construction of a model or map of the environment).</p>	<p>The capabilities of RISs for these applications and the expected performance as a function of their size, sub-wavelength structure, and near-field vs. far-field operation constitute an open research problem.</p> <p>In addition, radio localization and mapping can be considered to be important enablers for realizing important communication-related tasks.</p>	

연구개발 동향 및 이슈

◆ 지금까지 이동통신방식은 주어진 무선채널 환경에서 송수신기 구조 최적화로 최적 성능을 확보하였지만, 주어진 무선채널환경을 재구성 가능한 스마트 무선채널 환경으로 만드는 것과 아래 use case에서 그 스마트 무선환경을 송수신기 구조와 동시에 최적화하여 성능 개선을 할 수 있는가 그리고 현실적으로 가능한가?

- nLOS로 인한 품질 저하, 국부적인 음영지역 등에 대한 커버리지 향상
- 간섭 감소로 인한 성능 향상 다중 사용자 저수익 이차 채널 액세스 spatial modulation 등

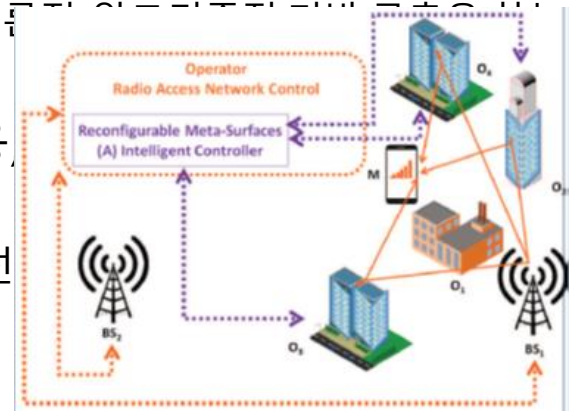


◆ 스마트 무선환경 실현을 위해 RIS의 기본이 되는 Metasurface 실현은 가능한가?

- 현재, 커버리지 향상을 위한 MIT의 RFocus prototype, NTT DOCOMO의 Smart glass prototype 등이 있지만, 균일화되고 macroscopic한 모델기반 접근(표면 susceptibility 혹은 임피던스)으로는 Metasurface의 실제 실현에 한계가 있다.
- 따라서, 무선망의 분석/최적화를 위해 Metasurface의 단위 셀에 대한 간단한 모델에서 시작하여 Metasurface 구조에 대한 동등한 전자기파 기반 회로 모델 (단위 셀간 mutual coupling을 크기, 셀간 간격, 공간 배치의 함수로 표현)이 필요
 - ※ 2021 년 5 월 시작 예정인 유럽의 PathFinder 프로젝트에서는 지능적 Metasurface로 스마트 재구성 무선 환경으로 전환시키기 위해 통신 이론, 물리학 및 전자기학의 도구를 활용하는 다학제 간 방법론을 도입하여 RIS 지원 무선망의 이론적 기반을 확립하는 것이 목표이다.

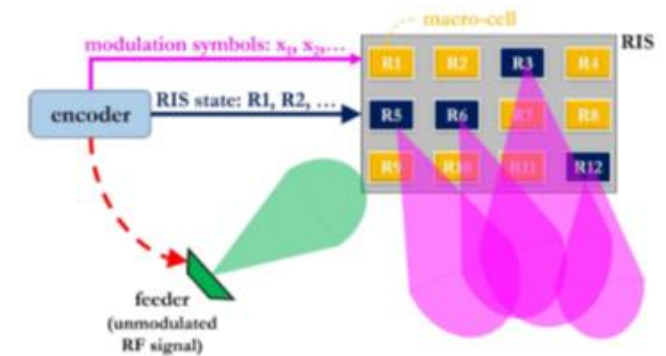
◆ 현재 트래픽 수요 대처와 도심/실내 서비스 커버리지 확보에 mid-band/mmWave 사용, 적용은 CAPEX와 OPEX 측면과 실시간 대응에서 문제를 어떻게 해소할 것인가?

- RIS로 nLOS와 국부적인 음영 지역에 통화 품질 향상 실현할 수 있지만,ダイナ믹하게 변화하는 무선할 수 있는 채널 추정, 자원 할당과 기계학습 프레임워크 부재?



연구개발 동향 및 이슈

- ◆ RIS는 스마트 reflector, 빔 스티어링, 빔 포밍, spatial modulation과 인코딩, 다중 스트리밍 전송 등을 포함하는 다양한 목적으로 사용될 수 있지만, 적용되는 특정 응용에 대한 궁극적인 성능 한계를 아직 모른다.
- ◆ 폭증하는 트래픽에 대처하기 위해 송수신기에서 최적 변복조와 채널부호화 그리고 Massive MIMO 기술이 표준화되었지만, 채널 용량을 극대화하기 위해 RIS를 사용 혹은 무선채널을 고려한 최적 설계는 무엇인가?
 - RIS를 전자기파 레벨에서 직접 동작하는 Spatial Modulation과 encoding은?
 - 경제적으로 실현가능한 저 복잡도의 RIS 기반의 Massive MIMO 설계는?



- ◆ RIS 기반 스마트 무선환경에서 성능 한계 분석, 최적화, 평가를 위한 무선채널은 무선환경에 따라 재구성되므로 기존의 무선채널 모델을 사용할 수 없으므로 새로운 무선채널 모델과 시스템레벨 시뮬레이터 필요

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연구개발 동향 및 이슈

- ◆ 최근 학술적으로 재구성 가능한 Metasurface 연구가 증가하고 있지만 여전히 Metasurface 해석과 최적에 대한 통신훈이론 관점에서 연구 문제들;
 - (1) 재구성 가능한 Metasurface을 무선 네트워크에 통합하는 방법은? 대규모 무선 네트워크에 공간적으로 분산되어있는 재구성 가능한 Metasurface의 모델링, 분석, 시뮬레이션, 최적화 및 조정하는 방법은 무엇입니까?
 - (2) 재구성 가능한 Metasurface이 있을 때 무선 네트워크의 궁극적 성능 한계는 무엇입니까?
 - (3) 실제로 그러한 성능 한계를 달성하는 방법은 무엇입니까?
- ◆ (현 Metasurface에 대한 macroscopic한 모델기반 접근(표면 susceptibility 혹은 임피던스)으로는 Metasurface기반 반사 안테나 실현 한계) 무선망에 대한 분석/최적화를 위해 반사 Metasurface의 단위 셀에 대한 간단한 모델에서 시작하여 반사 Metasurface 구조에 대한 동등한 전자기파 기반 회로 모델(단위 셀간 mutual coupling을 크기, 셀간 간격, 공간 배치의 함수로 표현) 연구 필요