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The Potentials, Challenges, and Future Directions of On-Chip-Antennas for Emerging Wireless Applications–A Comprehensive Survey

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ABSTRACT The ever-growing demand for low power, high performance, cost-effective, low-profile, and highly integrated wireless systems for emerging applications has triggered the need for the enormous innovations in wireless transceiver systems, components, architectures and technologies. This is especially valid for the antenna which is an integral component of the wireless transceiver systems and contributes significantly in determining their overall performance. Antenna-on-Chip (AoC) is an alternative antenna technology, which has drawn a substantial attention in recent days because of its various benefits over off-chip antenna technology. A few of these benefits include miniaturization, low power, low cost, and high integration of the wireless modules. Motivated by these valuable advantages and to unveil the true potential of the AoCs, this article presents, for the first time, a comprehensive survey of the suitability, advantages, and challenges of the AoCs for the emerging wireless applications such as 5th generation (5G) Wireless Systems, Internet-of-Things (IoT) Wireless Devices and Systems, Wireless Sensor Networks (WSNs), Wireless Interconnects, Wireless Energy Transfer, Radio Frequency (RF) Energy Harvesting, Biomedical Implants, Unmanned Aerial Vehicles (UAVs), Autonomous vehicles, Innovative characterization methods for Integrated Circuits (ICs) and Antennas, and Smart City. In addition, this article presents the current state-of-the-art of the AoC's applications by classifying their applications in Millimeter-Wave (MM-Wave) band, Terahertz (THz) band, and low-frequency bands. The article also investigates and describes some useful methods for the mitigation of the challenges and issues posed by the emerging applications for the realization of the AoCs in a systematic manner. A concise description of the future directions of the AoCs with respect to each emerging application is also a part of this article. It is expected that this well-structured and organized survey will not only act as an excellent source of scholarship for the relevant research community, but also open up a world of novel research opportunities.

INDEX TERMS Antenna measurement, autonomous vehicles, biomedical implants, CMOS, drones, IoT, ICs, ICs characterization, MM-Wave, on-chip-antennas, RF energy harvesting, smart city, system-on-chip, SiGe BiCMOS, THz, unmanned aerial vehicles, wearable antennas, wireless sensor networks, wireless energy transfer, 5G.

I. INTRODUCTION

The last decade has witnessed an explosive advancement in the design of low-profile, power-efficient and cost-effective transceivers for wireless applications. Besides tremendous developments in ICs, transistor scaling and fabrication processes [1]–[3], this progress is essentially credited to the efficient integration and packaging methods [1]. The role of such integration methods is expected to proliferate in the future, because of the emergence of innovative applications such as 5G wireless technology [4]–[14], IoT wireless devices and systems [15], WSNs [16]–[20], and Smart Cities [21], [22],

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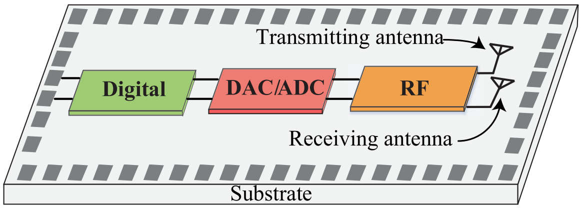

FIGURE 1. SoC based integration method: All sections of the wireless system including antennas are integrated on the same substrate, thus eliminating the need of lossy bond wires in contrary to other integration methods and resulting in a more compact, low loss, low power and cost-effective wireless modules.

etc. Recently, System-on-Chip (SoC) integration technique has drawn an ample attention to the wireless applications over the alternative integration methods, i.e. Multichip module and System-in-Packaging (SiP) owing to its multitude of valuable benefits. A few of these advantages include low cost, miniaturization, low power consumption and less complexity for the wireless modules. All the sections (digital, Analog-to-Digital Converter (ADC)/Digital-to-Analog Converter (DAC), RF front-end, and antennas) of a modern SoC based wireless system are placed on the same substrate as shown in Figure 1. The antenna of such a system is called as On-Chip-Antenna (AoC). Proposed by [23], AoC offers numerous highly desired advantages over off-chip antennas. Some of these advantages include: (i) a relaxed requirement in terms of the impedance matching network between the AoC and other electronic components of the RF front-end section, thus saving the cost and hardware [1] and improving the signal-to-noise ratio (SNR) of the system [24], (ii) a decrease in the requirements of the system's power and the design efforts [2], [25]–[28], (iii) ICs solutions with less complex packaging requirements [26], [29], and (iv) an extra design flexibility to the designers by providing a co-design opportunity of the antenna and other components of the transceiver along with the superior beam-shaping features and a short antenna design cycle [28], [29].

As far as the technology is concerned, Silicon (Si) based technologies (Complementary Metal Oxide Semiconductor (CMOS) and Silicon Germanium (SiGe) Bipolar CMOS (BiCMOS)) have become an attractive choice for the AoC's design nowadays because of their variety of benefits such as reduced cost, small chip-size, low power, high integration level, and the accessibility to several processes. Moreover, the unity-gain frequency (f_t) and unity-power-gain frequency (f_{max}) of MOS transistors have now been pushed well beyond 300 GHz in some SiGe CMOS processes [79], thus enabling the realization of AoCs design for MM-Wave and THz applications. In fact, the value of f_{max} for the MOS transistors has now reached up-to 570 GHz [30], which is achieved by integrating the Infinion's 130 nm process with the IHP's advanced SiGe HBT module with an elevated extrinsic base and non selective epitaxial-bases deposition [31]. Because of these stupendous benefits, a large majority of recently designed AoCs have utilized Si technologies, especially SiGe BiCMOS. This is evidenced by Table 1, 2, 3, and 4 which show the current state-of-the-art of the AoCs with respect to the application areas. However, the low resistivity (10 Ω-cm) and high permittivity ($\epsilon_r \approx 11.7$) values of Si-based technologies, especially of CMOS, are unable to provide the AoCs whose performance is at par with the off-chip antennas [1]. As a result, a trend on the use of other technologies has also been witnessed as one of the solutions to this problem; although their use is limited as compared to CMOS and SiGe BiCMOS technologies. Substrate-on-Insulator (SOI) CMOS is one of such technologies and is utilized for the AoCs design because of its high resistivity substrate [32] that results in a significant improvement in the performance of SOI-CMOS based AoCs. However, SOI-CMOS is associated with the higher cost as compared to CMOS and SiGe BiCMOS technologies [2]. Gallium Arsenide (GaAs) is another alternative technology which boosts the AoCs performance due to its high resistivity substrate. However, this performance boost is obtained at the cost of higher chip-area in comparison with CMOS and SiGe BiCMOS technologies. Micro-electro-mechanical-system (MEMS) is yet another emerging technology that is preferred for AoCs design mainly because of its compatibility with Si-based technologies and the capability to enhance AoCs performance. Another technology in this respect is Glass integrated-passive-device (GIPD) which finds the application for AoCs design because of its low value of loss tangent compared to Si technologies [33] and thus GIPD based AoCs can offer better gain and radiation efficiency. This technology, however, is costly and lacks the benefit of high integration as compared to CMOS and SiGe BiCMOS technologies. Indium Phosphide (InP) substrate [34], [35] has also been used for the design of few AoCs because of its good performance at MM-Wave. However, InP lacks high integration benefits. Recently, one AoC using Magnesium Oxide (MgO) substrate [36] has also been reported because of high value of its substrate's resistivity. The MgO substrate, however, is not much favorable for highly integrated wireless systems in comparison with CMOS and SiGe BiCMOS technologies.

As far as antenna types and configurations are concerned, usually differential antennas are preferred as AoCs since the majority of the ICs have differential inputs and outputs [37] which makes the task of on-chip integration easy. Conventionally, the antennas have been categorized into several types and configurations. Traditionally, dipole, monopole, yagi-uda and loop antennas have been popular as an AoC and the selection of each of these is dictated by the set of requirements posed by a particular application [1]. However, a trend of using other antenna types as an AoC has been witnessed recently. The most recent antenna types along with their performance characteristics used as an AoC can be found in Table 1, 2, 3, and 4. Each of these antenna types possesses its own advantages, limitations and applications. For instance, Vivaldi antennas are getting popular in radar and array configurations due to high gain, wide bandwidth, and simple structure [38]. Moreover, the bandwidth of these

TABLE 1. AOC's applications in MM-Wave band (up-to 60 GHz): current state-of-the-art.

Ref.	Application Area	Technology/Process	Antenna Type	Freq. (GHz)	Peak Gain (dBi)	$\eta_{rad}(\%)$	BW (GHz)	$\|S_{11}\|$ (dB)	Contribution
[81]	Wireless Sensor Node	65 nm CMOS	Monopole	30,60	≈0@60 GHz, 11@30 GHz	Not reported	Not reported	Not reported	Presents a compact, low power, and light-weight dual-band wireless temperature sensor.
[82]	Sensors Network and Wireless Tagging	65 nm CMOS	Folded-Meandered Dipole, Dipole	24, 60	Not reported	28-35 @ 24 GHz, 41-46 @ 60 GHz	Not reported	Not reported	A novel, miniaturized, dual-band, wirelessly powered, and pad-less passive radio with a communication range of 50 cm.
[83]	Multi Gb/s Wireless Interconnect Contactless Connector	65 nm CMOS	Folded Dipole	60	Not reported	Not reported	Not reported	Not reported	Presents a short distance (<5mm), low cost, low loss, no mechanical connection, and high data rate based wireless interconnect method.
[84]	Wireless Network-on-Chip (WNoC)	High ρ Si	Dipole	26-40	1.69 dB	Not reported	6.7	-32.53 @ 31 GHz	Demonstrates a low power, high speed and small size WNoC transmission channel.
[85]	High Resolution 3-D Imaging	130 nm SiGe BiCMOS	Bow-tie	30	Not reported	19.1	Not reported	Not reported	Suggests a novel method for achieving low profile, simple and accurate phase locking based 3-D imaging radar.
[86]	Q-Band Wireless Communication	180 nm SOI CMOS	Frequency Reconfigurable Monopole with On-Chip Switches	29-51	3.3 @ 45 GHz	Not reported	21.5	-30 @ 45 GHz	Proposes a novel AoC which enables high data rate, low loss, and enhanced bandwidth for the system.
[87]	RFID SoC	90 nm CMOS	Dipole	24	-7.6	Not reported	Not reported	Not reported	Proposes a novel, low cost, and low profile RFID SoC.
[88]	IoT	65 nm CMOS	Tuning-fork like Antenna	60	0.69 dB	28.57	19.7	Not reported	Demonstrates a miniaturized, and low power IoT transmitter.
[38]	MM-Wave Radar and Microwave Imaging	180 nm CMOS	Exponential TSA Vivaldi	60	-0.4	30	20	-23	Proposes an efficient, and compact AoC-suitable for a miniaturized array design.
[59]	WPAN	CMOS	Monopole	60	-4.96	Not reported	25	-27.7	Presents a low profile , and easily Integrable (with front-end) AoC.
[89]	Chip-to-Chip Wireless Communication	CMOS ground supply planes with 7 kΩ-cm ultra-thick Si substrate	Slot	60	Not reported	92	Not reported	-30	Presents a low profile , and easily Integrable (with front-end) AoC.
[90]	Wireless Sensor System	130 nm SiGe BiCMOS	Bow-tie	60	0.2	20.9	2.5	-18	Presents a compact, and low weight AoC for passive wireless sensor systems.
[91]	Q-band Broadband Applications	180 nm SOI CMOS	Dipole	29.5-51	2.2	60.2	21.5	-30	Proposes a high performance, and frequency reconfigurable AoC where two switches enable frequency re-configurability.

antennas can be enhanced by the stacking [39]. However, the Tapered Slot Antenna (TSA)-a type of Vivaldi antennas-faces a severe design trade-off. For better radiation characteristics, the width of TSA should be greater than $\frac{\lambda}{2}$ where λ is the wavelength. The disadvantage of this requirement is lesser compactness of the antenna which is essential for several practical applications such as MM-Wave imaging arrays. Further, among two types of bow-tie antennas, fractal antennas are compact as compared to non-fractal antennas from a design point of view [39], [40] which in turn means less budget. In addition, bow-tie antennas have a wider bandwidth compared to the patch antenna. On the contrary, monopole antennas are not a victim of substrate cavity and ground plane loss problems because of their reduced physical size, which causes less current penetration in the substrate [24], and are relatively good candidates for on-chip applications. Besides antenna types mentioned in Table 1-4, few other antenna types have also got attention in recent days. These include open-ended loop [41], leaky-wave [3], [42], horn [43], fractal bow-tie [39], [40], coil [44], and inductive loop antenna [45].

Despite several conspicuous advantages and ubiquitous applications, the design of the AoCs offers multiple challenges too. First, their performance metrics, e.g. the gain and radiation efficiency are not at par with the off-chip antennas owing to the fact that Si substrate is not well-suited for their design. The low resistivity (12.5 Ω-cm) and high permittivity ($\epsilon_r \approx 11.9$) values of the Si substrate [1], [3], [46], as shown in Figure 2 for a typical six metal layer CMOS process environment, are responsible for this performance degradation. The small thickness between metal layers ($\approx$ 14 μm), thick Si substrate ($\approx$275 μm), and low resistivity of the Si substrate (Figure 2) cause a large proportion of AoC's electromagnetic waves (EM) to travel towards the substrate. This results in a degradation in AoC's gain [1]. Likewise, high permittivity permits a significant fraction of AoC's EM waves to get absorbed into the Si substrate instead of

TABLE 2. AOC's applications in MM-Wave band (above 60 GHz): current state-of-the-art.

Ref.	Application Area	Technology/Process	Antenna Type	Freq. (GHz)	Peak Gain (dBi)	$\eta_{rad}(\%)$	BW (GHz)	$\lvert S_{11}\rvert$ (dB)	Contribution
[93]	Power Generation and Beam-Steering	65 nm Bulk CMOS	Travelling Wave Radiator (Array of 2 $\times$ 2)	Near 200	Not reported	Not reported	Not reported	Not reported	Proposes a novel beam-forming method, and mitigates the effect of the surface waves in the lossy Si substrate.
[94]	High-Speed Wireless Clock Synchronization	130 nm SiGe BiCMOS	Planar Bow-Tie	54	Not reported	60	Not reported	Not reported	Develop a novel receiver with lens integrated AoC which detects the picosecond EM pulses.
[95]	Passive RFID Chip	130 nm SiGe BiCMOS	Patch	61	Not reported	Not reported	22.8	Not reported	Presents a novel transceiver that achieves a record relative bandwidth of 38.6 % for SiGe based signal generator with VCOs.
[34]	MM-Wave Radar Imaging/OOK/Low Rate Impulse Radio	0.65 mm InP	DRA	V-band	Not reported	Not reported	Not reported	Not reported	Proposes compact resonant tunneling diodes and AoCs based wavelet transmitters without lossy transmission lines.
[96]	Near-field IoT	65 nm CMOS	Tuning-fork like	V-band	Not reported	Not reported	15	-20	Develop a novel, small form factor, and external components-free based transceiver.
[77]	Radar Sensor Packaging	SiGe BiCMOS	Integrated Lens	122	16.7	Not reported	2	Not reported	Presents an efficient, low cost, simple, and PCB processes complaint novel solution for radar SoC.
[97]	High Data Rate Short Distance Wireless Communication	130 nm SiGe BiCMOS	3-D Monopole	190	5	90	50	Not reported	Presents an innovative transceiver with large bandwidth and low power.
[32]	5G	45 nm CMOS SOI	Dipole	68	3.9 dB	82	Not reported	-28	Presents a high performance AoC and claims that SOI CMOS based AoCs can show performance comparable to the AiP at MM-Wave.
[32]	5G	45 nm CMOS SOI	Slot	68	3.8	83	Not reported	-29	Proposes an efficient AoC which can mitigate the standard CMOS based AoCs performance issues.
[32]	5G	45 nm CMOS SOI	Loop	68	3.7	79	Not reported	-25	Shows that SOI CMOS has potential to offer high gain AoCs.
[98]	Chip-to-Chip Wireless Communication	130 nm SiGe	3-D Monopole	200	4.9	90	60	<-24	Demonstrates an efficient, compact, and standard RF probes testable AoC.
[39]	Bandwidth Enhancement	130 nm SiGe	Stacked Vivaldi	180	> 0	Not reported	72	<-14	Proposes a method to enhance the system's bandwidth.
[99]	Amplitude Mono-pulse Radar	Seven Metal Layer SiGe Backend Process	Slot with Four Monopoles in between the Slot	120-130	Not reported	Not reported	10	-44	Present a compact radar with integrating AoC for sensing applications.
[80]	Novel Power Combining	SiGe Seven Metal Layers	Four Feed Slot with Monopoles	200-320	15	89	120	Not reported	Proposes small size, low loss, and a concentrated phase center based innovative power combining technique with just one AoC.
[100]	Differential Mode and Non-Contact Characterization of MM-Wave ICs and Devices	Not Reported	2 Differential Mode Double Slot with Lens Integrated	220-325	Not reported	Not reported	105	Not reported	Proposes a novel method which enables a low cost, robust, and non-contact testing of mentioned devices.
[101]	Next Generation Wireless Systems Mobile Terminal	7 Layers Si Process with 4 inch Wafer	3 x 3 Phased Array Topology of Bow-tie Dipole	35-70	Not reported	>60	35	Not reported	Proposes a compact, efficient, and cost-effective AoC array for 5G mobile terminal.
[88]	IoT	65 nm CMOS	Tuning-fork	120	1.69	47.6	23.4	Not reported	Proposes a novel receiver with low power, and small chip-area.
[40]	Chip-to-Chip Wireless Communication	130 nm SiGe	Slot Bow-Tie	200	4	Not reported	> 10	<-10	Demonstrates an AoC for up-to 100 Gb/s wireless interconnects.
[40]	Wireless Computer Board-to-Board Communication	130 nm SiGe	Half-Cloverleaf	200	> 0	Not reported	>10	<-12	Proposes an AoC which can mitigate the delay issues of wired systems.

TABLE 2. ***(Continued.)*** **AOC's applications in MM-Wave band (above 60 GHz): current state-of-the-art.**

[102]	Sub-Picoseconds Wireless Synchronization	130 nm SiGe BiCMOS	Broadband Bow-tie	30-100	Not reported	Not reported	70	Not reported	Presents a novel, ultra-short pulses based time transfer method, offering lowest ever time jitter for such systems.
[78]	High Data Rate Wireless Transmission, i.e. 5 G Mobile Terminal	130 nm SiGe BiCMOS	Not reported	240	20	Not reported	Not reported	Not reported	Proposes a miniaturized, low-cost, and simple AoC based fully integrated RF transmitter.
[79]	High Data Rate Communication Link	130 nm SiGe	Ring	240	26.4	Not reported	Not reported	Not reported	Proposes a high data rate link with novel, integrated direct conversion compact transmitter and receiver modules.
[103]	Antenna Domain Self-Interference Mitigation	45 nm SOI	Loop	60-75	Not reported	91.2	15	Not reported	Demonstrates a novel full-duplex transceiver front-end with multi-feed AoC for mitigating domain self-interference issue.
[104]	Array Applications	Standard CMOS	DRA Array	130	7, 8.2	Not reported	20	<-20	Presents miniaturized 2 × 1 and 4 × 1 arrays of on-chip DRA.
[105]	FMCW Radar	65 nm CMOS	Monopole feeding the patch	77	Not reported	Not reported	1.68	<-13	Proposes a novel packaging method using on-chip monopole for UAV applications.
[106]	W-band Applications (imaging, radar, biomedical, etc.)	130 nm BiCMOS	Double-Rhomboid Bowtie-slot	80-90	-0.58	Not reported	10	<-10	Proposes a novel AoC, which outperforms other W-band AoCs in terms of gain and miniaturization.

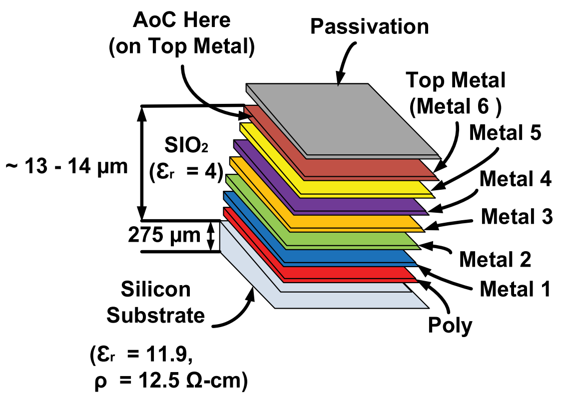

FIGURE 2. **A typical six metal layers CMOS process (3D view); AoC is designed using top metal. Low resistivity and high permittivity of Si substrate are the reasons behind AoC's degraded performance as compared to off-chip antennas.**

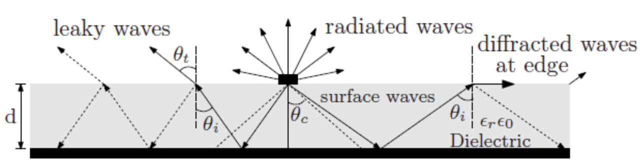

FIGURE 3. **The generation of surface waves for AoC which is placed on top of the grounded dielectric material [47].**

propagating into the air, thus deteriorating the AoC's performance. In addition, the low resistivity and high permittivity espouses surface waves or substrate modes which further affect the AoC's radiation characteristics. The effect of surface waves on AoC's radiation pattern can be seen in Figure 3 where the AoC is placed on a grounded dielectric material, i.e. substrate with a particular thickness, resistivity, and dielectric constant. It can be seen from Figure 3 that not all EM waves of the AoC are radiated into the air, but a fraction of these waves is also propagated to the ground plane where they are reflected and propagate to the dielectric-air interface. Depending on the angle of incidence of these reflected waves with respect to a critical angle (larger or smaller), these may either become leaky waves or totally trapped in the dielectric material, as shown in Figure 3. These trapped waves propagate as surface waves and are diffracted at the edge of dielectric material, thus distorting the radiation pattern of the AoC. Generally, this effect of low resistivity and high permittivity on AoC's performance is similar for MM-Wave, THz, and RF bands. Second, it is a tough job to characterize AoCs accurately and repeatedly since the traditional antenna measurement setups are unable to do so due to several limitations [48], [51]. Few of these constraints include: (i) the need for the replacement of x-y-z positioner of the conventional setup with the rotating positioner, (ii) low performance and lack in re-configurability/flexibility in the existing setups, (iii) the movement challenges posed by the antenna-under-test, (iv) the reflection and Electromagnetic Interference (EMI) issues caused by the metallic components of the measuring probe, (v) the shift in the resonance frequency of the AoC because of the capacitive impacts caused by the ground-signal-ground pads, and (vi) an uncertainty in the measurement results because of the residual currents of the substrate [50], [51]. Third, their layout, design and performance are often incompatible with respect to the process-specific design rules [2], [46], [52]. For instance, there is no provision of design rules for AoCs in modern Si processes, that makes it extremely difficult to verify whether

TABLE 3. AOC's recent applications in THz band: current state-of-the-art.

Ref.	Application Area	Technology/Process	Antenna Type	Freq. (THz)	Peak Gain (dBi)	$\eta_{rad}(\%)$	BW (GHz)	$\|S_{11}\|$ (dB)	Contribution
[118]	THz Indoor Wireless Communication	InP with 50 um thickness	Bow-Tie Antenna	.5	4	70	Not reported	-29	THz Resonant tunneling oscillator using AoC with higher data rates and larger BW.
[112]	WNoC	Graphene Patch Integrated with 180 nm CMOS	Square Patch	Dual band (2.15-2.2 and 2.56-2.6)	4.01 and 5.03	Not reported	0.05 and 0.04	-38	A CMOS process graphene compatible AoC.
[107]	THz Detector for Imaging	65 nm CMOS	Dipole	.278	-7	Not reported	Not reported	Not reported	Offers a method to realize low cost and low power THz detector.
[119]	Large Sized Arrays	SiGe HBT	Yagi-Uda	.314	Not reported	Not reported	Not reported	Not reported	Demonstrates low-power and high performance transmitter and receiver for large sized arrays.
[120]	Quintupler Design	65nm Bulk CMOS	Patch	.650-.730	-0.87	19	0.019	-30	A fully-integrated quintupler design with the AoC using CMOS process at THz band.
[113]	THz Imaging & Sensing	130 nm SiGe	2 x 2 Slot Array	.320	7.9	Not reported	0.045	-16	A high performance and compact AoC array with an innovative miniaturized feeding mechanism.
[111]	THz Systems (Internet of Nano-things	MEMS	3-D Metallic Helix with Microstrip Feed	4	17.6	Not reported	1.6	-32	An AoC which mitigates the low gain, large size, and narrow bandwidth issues at THz.
[121]	THz Radiating Source for Efficient Multi-pixel CMOS THz Cameras	65 nm CMOS	Loop/Ring	.610	7.35	53	.123	<-10	An AoC based radiating source having highest peak EIRP and total radiated power.
[122]	THz High Data Rate Communication and Imaging Systems	0.1 µm GaAs	DRA	.270	6.4	75	0.04	-16	Presents a high performance multiplier chain with an excellent spurious suppression response.
[123]	THz Wireless Communication	130 nm SiGe	Patch	.305-.375	3	50	0.070	Not reported	Proposes a novel, fully integrated, low cost, and compact transceiver with a highest tuning bandwidth.
[114]	Wireless Interconnects	65 nm CMOS	Substrate Integrated Waveguide	.55	2.8	22	0.020	-33	A compact, low loss, large bandwidth, and high quality factor based AoC with two modes excitation.
[110]	THz Image Sensor	180 nm CMOS	Folded-Slot	.850-1.05	>0	Not reported	0.2	Not reported	Proposes a low cost and highly integrated THz detector using AoC.
[115]	THz Applications	65 nm CMOS	Dipole	.235	0	63	0.081	-31	Presents a novel design which enhances the AoC performance with a miniaturized AMC structure.
[123]	THz Region Applications	130 nm SiGe BiCMOS	Patch	.305-.375	3	50	0.070	Not reported	A fully integrated transceiver.
[116]	THz Detection	180 nm CMOS	Slotted Patch	0.270-0.320	Not reported	75.18	0.050	<-25	Proposes a cost-effective, large bandwidth, and high gain detector using AoC.
[35]	THz Applications	InP	Slot	0.14	23.8	Not reported	0.078	-44	Presents a high gain and large impedance bandwidth AoC.
[117]	THz Imaging	180 nm CMOS	DRA 2x2 Array	.34	8.6	54	0.016	-30	Proposes a higher order mode DRA having high gain.
[36]	THz 4th Harmonic Mixer	MgO Substrate	CPW with Twin Slots	.640	19.9	Not reported	0.075	-4.5	4th harmonic AoC based mixer having good cost-performance compromise based benefit.

the designed AoC's layout is in accordance with the design rules or not. Fourth, there is no mutual computer-aided-design tool available where AoC and other components of the wireless IC can be designed [51]. This makes the overall antenna design cycle lengthy and tedious as several iterations among different tools need to be performed in order to make the design successful. Fifth, the AoC can interact electromagnetically with the nearby components of RF front-end, especially the inductors. The outcome can be a severe degradation in the performance of both, the AoC and the inductor [1], [53].

Today, the world is witnessing explosive advancements in the field of wireless communication, fueled by the emergence of innovative applications such as 5G, IoT, WSNs,

TABLE 4. Recent application areas of AOC's in low frequency band (lower than MM-Wave band): current state-of-the-art.

Ref.	Application Area	Technology/Process	Antenna Type	Freq. (GHz)	Peak Gain (dBi)	$\eta_{rad}(\%)$	BW (GHz)	$\|S_{11}\|$ (dB)	Contribution
[128]	Bio-Telemetry	180 nm CMOS	Meander line Microstrip Patch	2.45	-14	Not reported	0.3	-47.26	Proposes a highly miniaturized AoC for implantable devices (Chip area=10.45 mm^2).
[129]	Electromagnetic Energy Harvesting	180 nm SOI CMOS	Dipole	8-10	Not reported	21	Not reported	Not reported	A miniaturized AoC based system with reduced cost, chip-size, and less packaging issues (Chip area=2.22 mm^2).
[126]	GPS and RFIC for Wrist and Wearable Communication Applications	180 nm CMOS	Meander Line by Loop	1.575, 2.4	Not reported	Not reported	Not reported	Not reported	Presents an AoC based RFIC which facilitates the patients to contact the health care center and show location of the ambulance (Chip area=1.21 mm^2).
[130]	Inter-Chip Data Transmission/Wireless Interconnect	65 nm logic CMOS	Dipole	10	Not reported	Not reported	5.9	-47	Low power UWB impulse radio which transmits and receives the 2-Gb/s data at a distance of 10 mm (Chip area=1.8 mm^2).
[131]	Bio-Medical Implants	180 nm SOI CMOS	Loop	2.75	Not reported	Not reported	Not reported	Not reported	Proposes a novel design which is immune to the AoC misalignment or the variations in nearby biological tissues (Chip area=2.56 mm^2).
[132]	Wireless Clock Distribution	CMOS	Dipole	12	Not reported	Not reported	Not reported	Not reported	Proposes a novel method which introduces lesser delay than the existing methods (Chip area=16 mm^2).
[124]	Wirelessly Powered Bio-Medical Implants	180 nm CMOS	Dipole	8-10	Not reported	Not reported	Not reported	Not reported	Presents a battery-less miniaturized pacemaker chip with a wireless powering range of 2 cm (Chip area=NA).
[133]	IoT/Biomedical	180 nm CMOS	Dipole	1.46	Not reported	0.6	Not reported	Not reported	Proposes a miniaturized, battery-less , and wirelessly-powered transmitter with a data rate of 50 Mbps (Dipole length=3.9 mm).
[133]	Wireless Power Transfer	180 nm CMOS	Dipole	7	Not reported	13	Not reported	Not reported	Demonstrates an energy harvesting receiver for wirelessly powering-up the low power transmitter (Dipole length=3.9 mm).
[134]	Phased Array Transceiver	180 nm CMOS	Folded Monopole	15-18	0	Not reported	3	Not reported	Proposes four low cost and highly integrated transceivers with one AoC for each which achieves an EIRP value of 14 dBm (Chip area=NA).
[135]	RFID	180 nm CMOS	Double-Loop	5	-26	Not reported	Not reported	Not reported	Presents a novel pad-less RFID architecture with AoC which solves the design trade-offs issues (range, cost, and size) of conventional RFID (Chip area=2.52 mm^2).
[44]	RFID for IoT/Low-Power Sensors	65 nm CMOS	Coil	5.8	Not reported	Not reported	Not reported	Not reported	Demonstrates a novel, compact, and high performance power harvesting RFID radio with only single antenna for up and down link (Chip area=NA.
[127]	UHF RFID Based Contact-less Wafer-level Testing	CMOS Wafer	Post-Processed Coil	.865	Not reported	Not reported	Not reported	Not reported	Proposes a compact and cost-effective method for a contact-less wafer level testing (Chip area=0.455 mm^2).
[136]	Wirelessly Powered Dielectric Sensor	180 nm SOI CMOS	Dipole	9.8	Not reported	30	Not reported	Not reported	An innovative dielectric sensor, wirelessly powered by AoC for sensing different dielectric materials such as oil and epoxy (Dipole length=3.9 mm).

smart city, wireless energy transfer, RF energy harvesting, biomedical implants, UAVs, autonomous vehicles, etc. The success of these ground-breaking applications is vitally subject to the enormous innovations in the wireless transceiver architectures, systems, components, and technology choices which could ensure low-power, low-profile, cost-effective, and high-performance wireless solutions. Keeping this in view and knowing the remarkable benefits of the AoCs, an immediate need arises to assess the potential of the AoCs for the emerging and future applications. Considering this

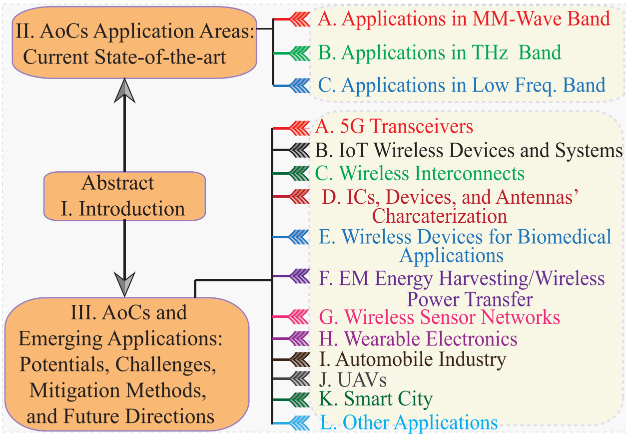

FIGURE 4. Graphical outline and contributions of the paper.

in the mind and finding a void in the literature, this paper presents a comprehensive survey on the suitability and the potentials of the AoCs for the evolving application domains for the first time. In addition, concise detail of the challenges posed by each application domain to the realization of the AoC is part of the article. These challenges lead to a variety of open research problems that need to be solved in order to pave a path of the AoCs for these applications.

The paper is organized as follows: Section II delineates the recent state-of-the-art related to the AoC's application areas. The detail of the AoC's potentials for few important emerging and future application areas along with the challenges is part of section III. Techniques for the mitigation of the design challenges and issues posed by these applications for the AoCs are also explored and described in this section. A brief detail of the future directions in this regard is also a part of this section. The paper ends with the conclusion section. A graphical representation of the paper's outline is also presented in Figure 4 in order to facilitate the readers for an easy follow-up of the paper. The graphical outline also highlights the contributions coming out of this work.

II. ON-CHIP-ANTENNAS AND APPLICATION AREAS: CURRENT STATE-OF-THE-ART

The survey of the recent literature shows the use of the AoCs for a diverse set of innovative applications. In this paper, the application areas of the AoCs have been divided into three categories based on their operating frequency bands: MM-Wave band, THz band, and low-frequency bands. The detail of the AoCs applications in each category is provided below.

A. APPLICATIONS IN MM-WAVE BAND

Table 1and 2 show the current state-of-the-art of the AoC's applications in MM-Wave band. The MM-Wave band (30-300 GHz) is one of the most attractive frequency bands for the design of the AoCs because of two main advantages. First, the AoC at MM-Wave consumes less chip-area due to its small form-factor. Second, the recent innovative developments in f_t and f_{max} of Si-based transistors, which have now surpassed 300 GHz due to a remarkable scaling, have made the use of Si technologies promising for the design of the MM-Wave band AoCs. In addition, the significance of MM-Wave band AoCs has been enhanced because of the viability of the antenna beam-steering functionality at MM-Wave, which has become ubiquitous for a multitude of contemporary applications such as 5G systems [54]–[56]. Consequently, a growing trend has been witnessed in the use of MM-Wave band for a variety of practical applications and the AoCs, being a perfect candidate, have also become pervasive in this band. Table 1 and 2 demonstrate the widespread use of the AoCs in MM-Wave band for a multifaceted set of innovative applications in recent years.

Table 1 and 2 also reveal that several MM-Wave bands are promising for the implementation of the AoCs. One of such widely used band is 60 GHz since the unlicensed 60 GHz band is suitable for various applications such as high-speed short range wireless communication [57], [58], wireless personal area network (WPAN) and broadband communication [25], [33], [37], [38], [41], [59]. The Wireless Gigabit (WiGig) standard also comes under the umbrella of the unlicensed V-band (57-64 GHz) [60]. In addition, 60 GHz is also one of the potential candidates for 5G systems [61]. Moreover, 60 GHz band has also been utilized for the AoCs based WSNs, IoT, and chip-to-chip communication applications. The AoCs for wireless chip-to-chip communication is gaining increasing attention at various MM-Wave bands [40] and the clock distribution to the microprocessors is one of the most promising examples in this domain.

In addition, it can also be observed from Table 1 and 2 that MM-Wave radars are another attractive application for the AoCs which are becoming prevalent for the various applications such as automotive, remote sensing, imaging and security systems [26], [62]–[69]. IoT and 5G are two other recent MM-Wave band applications for which few AoCs have been proposed. Several MM-Wave bands are considered one of the potential candidates for the 5G applications due to the availability of an abundant bandwidth and high data rate. Few of these bands include 26 and 28 GHz [70]–[72], 32 and 37 GHz [72], 33 GHz [73], 36 Hz [74], 38 GHz [75], 39 GHz [13], [61], 45 GHz [75], and 57-70 [74]–[76]. MM-Wave bands with the help of the AoCs have provided compact, economical, low-power, large bandwidth and high data-rate based IoT devices and systems; radio-frequency-identification (RFID) is one example of such devices. Beam-steering, power combining, and contact-less measurements of ICs are some other novel MM-Wave applications which have recently been empowered by the AoCs. In order to provide further insight about the MM-Wave AoCs with respect to the current state-of-the-art, self-explanatory plots of the references are shown in Figures 5 and 6, which present the relationship of AoC's gain and bandwidth with chip area for different technology processes.

Furthermore, some other insightful information is also summarized in Table 1 and 2. First, the AoCs have helped substantially in the miniaturization, power minimization,

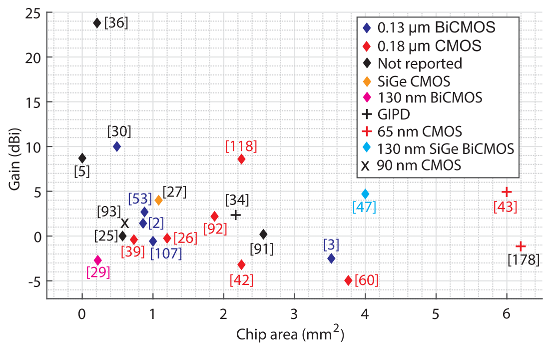

FIGURE 5. Plot of references showing the effect of MM-Wave AoCs' chip area with respect to the gain at different technology processes.

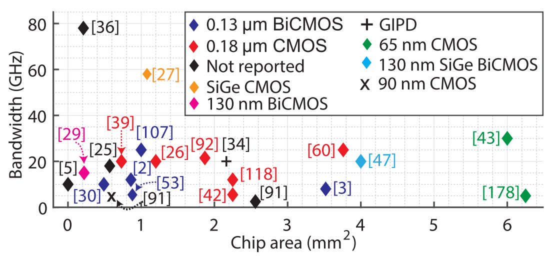

FIGURE 6. Plot of references showing the effect of MM-Wave AoCs' chip area with respect to the bandwidth at different technology processes.

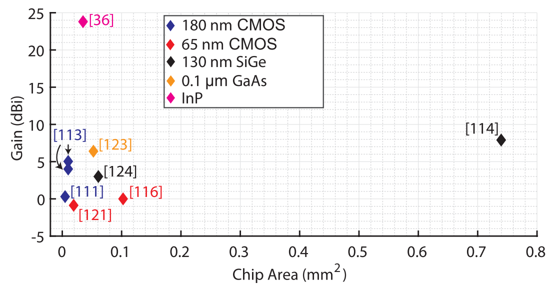

FIGURE 7. Plot of references showing the effect of THz AoCs' chip area with respect to the gain at different technology processes.

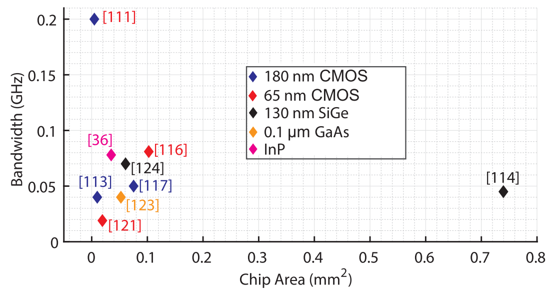

FIGURE 8. Plot of references showing the effect of THz AoCs' chip area with respect to the bandwidth at different technology processes.

cost reduction, and high integration of all MM-Wave based applications and the primary reason behind these benefits is the use of Si-based technologies, especially CMOS and SiGe-BiCMOS technologies. Second, a large majority of the AoCs has been designed in integration with the RF front-end of various systems. Few standalone AoCs have also been proposed. Third, the gain of a large proportion of the MM-Wave AoCs is low except the AoCs of [77]–[79] because of the use of the Si lens, and of [80] due to the use of high-resistivity substrate. This degraded gain pushes the need for the use of gain enhancement methods for these AoCs. Fourth, a couple of dual-band, two frequency re-configurable AoCs and two AoC based arrays have also been presented which underscore the significance of the AoCs. Fifth, InP, SOI CMOS and high resistivity substrates have also been utilized for the design of the MM-Wave AoCs in order to boost the performance of the AoCs in comparison with the CMOS and SiGe BiCMOS technologies.

B. APPLICATIONS IN THZ BAND

Table 3 lists the current state-of-the-art of the AoCs applications in the THz region (0.14 THz–4 THz). The THz band is another favorable band for the AoC's design. The reasons include smaller antenna size at THz frequencies and the viability of low-cost CMOS technology in the THz region due to the remarkable progress in the cut-off frequency of the MOS transistors [107]–[109]. As a result, the AoCs have been proposed for a myriad of THz region applications in recent years as evidenced by Table 3. Table 3 demonstrates that THz imaging, sensing and detection has been one of the leading applications with respect to the AoCs implementation because of the low cost and low-profile benefits. THz short-range wireless communication is another attractive application domain for the AoCs design since it ensures high data rate, large bandwidth and miniaturization for the communication systems. Two other promising THz region applications for which AoCs have been proposed include wireless Network-on-Chip (WNoC), and wireless interconnects which are capable of mitigating the issues faced by conventional wired networks and interconnects, respectively.

Table 3 shows that the maximum frequency in the THz range for which AoC has been designed is 4 THz [111]. In addition, InP, Graphene, GaAs, MEMS, and MgO substrates have also shown their potential for the design of THz AoCs besides Si technologies. The gain of THz region AoCs is low except the AoC of [111] because of the use of MEMS method, the AoC of [35] due to the use of InP technology, and the AoC of [36] because of the use of high resistivity MgO substrate. One THz AoC based array and a dual-band AoC have also been proposed. Apart from the AoCs of [35], [111]–[117], all other THz AoCs of Table 3 have been designed for other systems instead of a standalone component. Plots of the references shown in Figures 7 and 8 elucidate the relationship of THz AoC's gain and bandwidth with chip area for different technology processes.

C. APPLICATION IN LOW-FREQUENCY BANDS

Besides MM-Wave and THz bands, the use of the AoCs for relatively low-frequency bands (lower than 30 GHz) is

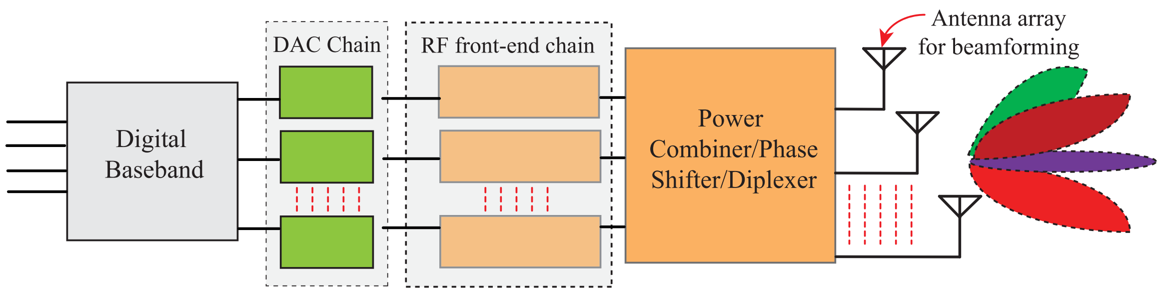

FIGURE 9. A simple example diagram of beam-forming based Massive MIMO 5G transmitter architecture: note the use of multiple antennas/antenna arrays. The PA will be a part of the RF front-end section. The massive MIMO based 5G receiver will also use antenna arrays.

also beneficial [124], [125]. Table 4 lists the current state-of-the-art of the AoCs applications along with antennas' performance characteristics and chip area in these bands. This Table shows that the most ubiquitous application domain with respect to the AoCs in these bands is IoT and its associated branches such as the electromagnetic and wireless energy/power harvester, and RFID. This is not surprising since the AoC ensures miniaturization, low-power, and low-cost benefits which are decisive factors for the success of these applications. In addition, electromagnetic energy harvesting is promising only in those bands which are being utilized for commercial applications because of the availability of sufficient electromagnetic energy to be harvested. A large number of such bands come in low-frequency region and thus the use of the AoCs for this application is very appealing. The biomedical implant devices are another dominant application avenue in these bands which have utilized the AoCs in order to achieve compact, cost-effective and low-power solutions. A pervasive application in these bands is inter and intra chip wireless communication. The use of the AoCs for this application mitigates the delay issues associated with the conventional metal interconnects. The AoCs for the promising phased array applications have also been proposed in this band. One AoC for the wearable applications has also been presented [126]. Likewise, one AoC for the contactless testing of the ICs in the fabrication phase has also been proposed [127].

It can also be observed from Table 4 that the gain of almost all the AoCs designed in these bands is low. In addition, they have been designed as a part of other wireless systems. As a result, the gain of a majority of the reported AoCs is not mentioned since it is extremely difficult to measure AoC's gain in integration with other components. Also, all of them have been designed using Si technologies (CMOS, SiGe, and SOI CMOS) which are the optimized technology choices for the AoC. Whereas, the lowest frequency for which the AoC has been reported is 865 MHz.

III. ON-CHIP-ANTENNAS AND EMERGING APPLICATIONS: POTENTIALS, CHALLENGES, MITIGATION TECHNIQUES, AND FUTURE PROSPECTS

There are several emerging applications for which the use of the AoC is very attractive because of its multiple valuable benefits. The use of the AoCs for each application is subject to a set of tough challenges too, which needs to be addressed prudently. This section describes the potentials and advantages of the AoCs for the emerging applications along with their associated challenges. A brief detail of the methods to overcome the challenges for each application is also a part of this section. It is obvious that each potential opens up the doors for the vast research opportunities and the solution of the challenges leads to a promising future direction.

A. TRANSCEIVERS FOR 5TH GENERATION WIRELESS SYSTEMS

5G transceivers are undoubtedly the most prominent emerging application for the AoCs. The ever-escalating demand for high data rate, large bandwidth, and low latency puts severe constraints on 4th Generation technology to meet the future wireless requirements, thus envisioning a 5G technology, which will provide high throughput, more spectrum-especially at MM-Wave, high capacity, low power, and low latency [4]. Novel AoCs and AoC based arrays, due to their smaller wavelength (λ) at MM-Wave, are well suited for 5G high-performance wireless nodes [101], especially for 5G mobile terminals. The potentials and advantages of the AoCs for this application with their related challenges are described below.

1) POTENTIALS

- **Suitable for Massive-MIMO architecture:** Massive multiple-input-multiple-output (Massive-MIMO) has obtained the status of a key enabling architecture for the MM-Wave 5G systems [137]–[139]. Massive-MIMO based 5G transceivers need antenna arrays to perform the coherent beam-forming function [140], [141] as shown in Figure 9. The budget and size, however, have been two major bottlenecks for the commercial level realization of the antenna arrays for this application and AoCs can overcome these limitations.
- **Mitigate the cost and chip area issues of massive-MIMO based 5G systems:** Since the 5G is yet in the evaluation phase, the question of the best transceiver architecture is an open debate. Three transceiver architectures have been a topic of the main discussion in the recent literature. These include analog, digital and

hybrid architectures [142]–[144]. In these architectures, the transmitter of massive-MIMO based 5G systems comprise of several power amplifiers (PAs) as shown in Figure 9. In order to efficiently combine the power coming out from different PAs of such system, the technique of spatial combining using antenna arrays is better due to its low loss benefit compared to other methods; but the major unresolved challenge associated are; large chip-area and high cost [6], [8], [137], [145]. Si technologies based AoCs are capable of mitigating both of these issues quite superbly.

- **Enhance the power efficiency of 5G transceiver system:** The approach described in Figure 9 is also superior in terms of power efficiency of the overall 5G transceiver system because of the use of multiple low power PAs instead of only one high power PA. This power efficiency, consequently, results in longer battery life and relaxed thermal management requirements for the system. This is important to note that this approach has been enabled by the use of the AoC based arrays.
- **Relax performance burden on 5G transceiver components:** Another valuable advantage of the approach i.e. the use of Massive-MIMO for 5G transceiver with AoC based arrays and multiple PAs is the reduced precision required for the transmitter and receiver of 5G systems since low resolution ADCs such as 4-8 bits [146] or even 1 bit [147] may be adequate. The resolution of ADCs for such systems is directly related to their power consumption, i.e. their power consumption increases with a rise in their resolutions. In addition, low resolution ADCs demand less performance and precision from the RF front-end equipped with a large number of antenna arrays [146]. These facts have been verified by the authors in [146], [147]. Consequently, low resolution ADC means a lesser power consumption and a reduced precision requirement for the RF front-end of such system. The outcome of all this is the subsidized requirements of the most power hungry block of RF front-end, i.e. PA in terms of linearity which exhibits well-known trade-off with PA's power-efficiency, which is known as linearity-efficiency trade-off. In other words, the PA does not need to be as power-efficient as it has to be without this approach since low resolution ADC has already reduced the power requirements of RF front-end. Thus, PA can now improve its linearity in a more flexible way. Based on these arguments, it can be said that this approach has the capability to break the conventional PA's efficiency vs. linearity trade-off. In short, the performance relaxation for the massive-MIMO based 5G transceiver components is one of the major benefits of this technique and the AoC based arrays are the key facilitator in this regard [138].

2) CHALLENGES, FEW GUIDELINES FOR THE SOLUTIONS, AND FUTURE DIRECTIONS

- **Mutual coupling issue:** The issue of the mutual coupling for the AoC arrays based 5G mobile terminal transceivers will rise considerably as a large number of the AoCs will be placed in each other's vicinity to save the chip-area [139]. It is observed that the overall sensitivity of the array primarily depends on the mutual coupling of the antennas which ultimately affects the performance of both, the transmitter and receiver of such a system. For good performance, it is, thus, vital to explore the solutions of this issue such as the AoC's right configuration and the use of the decoupling structures. Besides this, novel techniques to mitigate the Electromagnetic and RF interference will have to be investigated. One such technique has been proposed in [148] which directs the designers to first design all the antennas together as a single working system, apply multiple EMI and RF interference methods to overcome these issues, and then integrate this system of all working antennas into the mobile unit cohesively. However, there is a dire need for novel methods for the mitigation of this issue in the future.
- **High-performance AoCs:** Another critical issue is of an enhanced link-loss at MM-Wave frequencies and thus a reduced range for 5G systems [7], [11], [149]. One useful way to overcome this issue is to enhance the performance of the AoC based array elements [10]. This poses a grave challenge to the AoC since the AoC's performance is already degraded because of the reasons mentioned in the introduction section and thus, it needs the employment of innovative antenna performance enhancement methods which usually come at the cost of extra hardware and budget. Few performance enhancement methods which can be used in this regard are summarized below:
  1) **The use of the artificial magnetic conductors (AMC) [150], and the variants such as the frequency selective surfaces (FSS) [28] and partially reflective surfaces (PRS) [151]:** In this method, the artificial magnetic conductor structure is designed between AoC (top metal, FIGURE 2) and Si substrate. The AMC behaves as a high impedance surface for the incident EM field coming from the AoC towards the Si substrate. The incident EM waves are reflected from AMC with a phase difference of 0° and these reflected EM waves interfere constructively with the incident waves. Consequently, the EM waves become stronger and get radiated by the AoC, thus boosting AoC's performance, i.e. gain and radiation efficiency. The variants of AMC include FSS and PRS which, like AMC, have the ability to control the transmission and reflection characteristics of the incident EM waves. The AMC based AoC at 60 GHz achieves a gain of 0.25 dBi, and radiation efficiency of 49 % [25].

The use of FSS in [3] for a 94 GHz AoC results in a gain of -2.4 dBi. The employment of PSR for a V-band AoC of [151] boosts the gain by 1.98 dBi and radiation efficiency by 17 % over the AoC without PSR. Other AMC and its variant based AoC can be seen in [41], [152].

2) **The application of the localized backside etching (LBE)/Micromachining method for the selective removal of the antenna substrate:** In this technique, the lossy Si substrate around the AoC is removed locally as a post-processing step [46]. The removal of lossy substrate enhances the performance of the AoC. This method has got special attention recently because of the availability of the built-in LBE facility in few SiGe BiCMOS processes. The use of LBE for a D-band AoC of [46] has resulted in an AoC with the radiation efficiency of 76 % and gain of 4.7 dBi. In order to mitigate the issue of chip's mechanical stability associated with this method, the authors in [62] have removed only a small portion of the substrate around 12 GHz AoC, which resulted in a gain of 6 dBi and radiation efficiency of 54 %. The use of a similar method in [156] for a 120 GHz AoC has provided a peak gain of 3-5 dBi. The employment of LBE for a 77 GHz AoC designed in [157] provides a gain value of 4 dBi.

3) **The enhancement of the equivalent dielectric of the antenna substrate:** Here, the idea is to enhance the equivalent dielectric of the antenna substrate to increase its performance. Three different methods are usually employed to increase the equivalent dielectric of the antenna substrate. The first method is the use of Si lens beneath the lossy Si substrate which enhances its equivalent dielectric and thus, mitigate the losses and surface waves issues associated with the substrate and boosts AoC's performance. After the fabrication, the Si lens is glued with the IC containing the AoC with the help of an adhesive material. This is the most widely used method for performance enhancement of the AoC which provides a substantial boost in AoC's gain and radiation efficiency. Various types of lenses are used for this purpose. In [158], the use of a bullet Si lens for 308-386 GHz AoC has provided the gain and radiation efficiency of 13.5 dBi and 90 %, respectively. Gain enhancement of 1 dBi has been obtained in [159] where the Si substrate has been post-processed to act as a lens for a 180 GHz AoC. Hemispherical lens is the most famous type of the lens which is used for this purpose. The use of hemispherical lens in [63] has provided boost of 15 dB in gain for 110-140 GHz AoC. Hemispherical lens based AoC designed in [108] has achieved a radiation efficiency of 42-52 %. The use of periodic lens is also reported in [160] which enhances the radiation efficiency of AoC by 20 %.
The second method in this category is the use of dielectric resonator antenna (DRA). To increase the dielectric of the antenna substrate, a low-loss dielectric material based DRA is placed above the AoC using a glue material with a suitable feeding structure. The outcome is an increase in the AoC's performance. The use of a higher order mode excited DRA for a 340 GHz AoC [161] gives a gain boost of 6.7 dBi. In [122], a higher order mode DRA based AoC provides an enhancement in the gain and radiation efficiency of 4 dBi and 22 % respectively. The spherical DRA based 69 GHz AoC of [162] achieves a gain of 8.4 dBi and radiation efficiency of 72. A D-band AoC of [163] based on DRA obtains a gain of 18.9 dBi and radiation efficiency of 45 %. Other examples include [122], [164]–[166].
The third technique is the use of artificial dielectric superstrate (ADS) or artificial dielectric layers (ADLs). The ADS is a high permittivity material which is inserted into the host material to increase its dielectric constant. The ADS and ADLs have the ability to prevent the generation of surface waves, and thus enhances the AoC's performance [167]. The ADS, whose permittivity value is near to Si substrate, is placed above a 94 GHz AoC in [168], which provides a gain value of 0.4 dBi and radiation efficiency of 67 %. About 6 dBi gain enhancement is obtained for a 320 GHz 4 $\times$ 4 AoC array with the help of a quartz superstrate in [169]. In [170], the utilization of ADS has provided a 2 dBi rise in gain for a 0.3 THz AoC. For a 60 GHz AoC of [171], the use of ADLs has resulted in the gain and radiation efficiency boost of 3.6 dBi and 32.5 %, respectively.

4) **The selective decrease in antenna substrate's conductivity:** This is achieved by means of two methods. The first method is Helium-3 Ion Irradiation. In this method, the selective Si substrate near the AoC is irradiated with the Helium-3 Ion Irradiation method in order to decrease its conductivity which in turn boosts the AoC's performance. The employment of this method in [172] for a 60 GHz AoC enhances the radiation efficiency by 43 %. In [173], the use of this method with a vertical reflector for a 140 GHz AoC resulted in a gain rise of 5 dBi. The second method through which conductivity of the substrate is decreased is Proton Implantation. The application of this method in [174] for a 60 GHz AoC enhances the transmission gain by 15 dB in E-plane and 14 dB in H-plane.

5) **The use of micro-electro-mechanical-system (MEMS) technology:** MEMS has secured significant attention to achieve high performance AoC because of various advantages which include low-cost, easy fabrication, compatibility with CMOS technology, and provisioning of nanometer level precision [111].

The use of CMOS compatible Polymer MEMS fabrication process in [24] for the design of 50-67 GHz AoC provides a gain of −2.5 dBi.

Besides above-mentioned methods, innovative performance enhancement methods which are less costly, consume smaller chip area, and are supported by the standard Si technology processes are the need of the hour.

- **Need for broadband, multiband and dual polarized AoCs:** As the 5G system will consist of different MM-Wave bands, the design of broadband and multiband AoCs is highly desired to save a significant chip area. This puts a serious challenge on the AoCs as achieving the desired performance at multiple frequencies is a tough task for the AoCs and is one of the promising future research domains. Another requirement for a 5G Massive-MIMO based transceivers is to support dual-polarization communication [9]. AoCs will have to play a pivotal role in order to enable dual-polarization communication. However, achieving dual-polarization for the AoCs is not a trivial task as it can degrade other parameters of the AoC. Because of this reason, already designed AoCs with dual-polarization are very few as evidenced by Table 1-4.
- **Accurate measurement of AoCs:** Another serious challenge for 5G Massive-MIMO based AoCs will be to perform accurate and repeatable measurement. More specifically, their on-air testing will be required for a successful working of the system. Unfortunately, the existing AoC's measurement techniques are unable to do so [175]. As AoCs are integrated on the same chip, their characterization through conventional ways is not possible due to several constraints mentioned in the introduction section of the paper. This pushes the need for innovative measurement setups and solutions. Few guidelines regarding such new testing techniques for 5G radio are provided in [176] which emphasize on the modular approach where the testing platforms, built with a combination of the software strategies and hardware components can facilitate the 5G antenna measurement. In addition, a novel off-chip antenna measurement setup based on a small UAV for 5G mobile systems has been presented in [177]. It is anticipated that this measurement method can become one of the best methods for 5G AoC testing in the future because of its on-air/on-spot measurement capability. Moreover, a good starting point can be the AoC's measurement methods and solutions mentioned in [51] which could lead to the innovative measurement methods for the 5G AoCs too.
- **Packaging Issues of AoCs:** Despite all the advantages, the packaging and integration of the AoCs with RF front-end offers some challenges too. For instance, to comply with the design rules of the modern nanoscale CMOS process nodes such as the requirement of dummy metals is very tough for the AoC design. Often, the compliance of these design rules degrades the AoC performance and radiation characteristics. This problem gets worsened when the AoC is integrated with the RF front-end. The readers are advised to consult [178] for further detail of few of such issues for 5G MIMO applications. In addition, packaging issues emerge when different performance enhancement techniques are applied to the AoCs. For example, the addition of the superstrate on the top of the AoC creates severe packaging challenges since the access of all other IO is only possible through wire-bond and flip-chip on the front side of the IC. One solution is the use of a wafer-scale method based on custom lithography as proposed in [179]. Another solution at MM-Wave is proposed and validated in [180], where high performance has been achieved with the help of the aperture coupling between on-chip ground-plane/feed slot and antenna-on-substrate. Few other solutions which have been proposed to mitigate the AoC's packaging issues include: the use of the optimized structures on the PCB of the IC package for 60 GHz FMCW radar [181], the proposal of a novel quad flat no-lead (QFN)-type packaging method for 122 GHz radar keeping in view the thermal, electrical, and mechanical requirements [77], the development of innovative packaging method based on a chip to microstrip interface/transition for a 77 GHz FMCW radar [105], and the proposal and design of a novel package which also acts as a superstrate for a 77 GHz AoC [182]. Besides these solutions, there is a dire need of other novel packaging solutions for the AoCs to pave a path to their dominance in the future.

B. IoT WIRELESS SYSTEMS

Wireless systems for IoT are another key emerging application well-suited to the AoCs. IoT based devices and systems, which are likely to become ubiquitous in the near future [15], will find applications in diverse valuable domains. The potentials and challenges of AoCs for this application are described below.

1) POTENTIALS

- **Provide compact, low cost, and power–effective IoT solutions:** Wireless devices will form a large proportion of IoT systems [15]. For these devices, the miniaturization, low power consumption and high energy efficiency are essential requirements [96]. Moreover, RF energy harvesting is a must requirement for a majority of these systems since the use of the battery is not feasible because of large size, maintenance cost, and various constraints such as the need of surgery for biomedical IoT devices. Thus, the AoCs have already shown their potential in this regard and have been summarized in Table 1- 4
- **Mitigate RFID limitations for IoT applications:** RFID is one of the widely used devices for the

implementation of the ultra-low power IoT applications and backscatter modulation technique is utilized. The two major limitations associated with this technique are large antenna size and lower bandwidth because of relatively low operating frequency. It is quite reasonable to use the MM-Wave band [183] for this application since the recent rigorous developments in Si-based technologies have made their use feasible for MM-Wave operation. A 61 GHz RFID radio transceiver front-end has also been designed which shows a state-of-the-art performance [95]. The benefits of these two systems can conspicuously be enriched with the use of the AoCs.

- **Support MM-Wave near-field IoT transceivers:** The realization of the near-field IoT transceivers puts stringent requirements in terms of chip-size and power efficiency. However, the low GHz existing wireless standards are unable to meet these demands. Moreover, these low GHz transceivers need external components and off-chip large size antennas which increase the form-factor and the cost of the transceiver. Most importantly, a true measure of the power efficiency of such systems is their energy-efficiency instead of the power consumption of the transceiver and the existing low GHz wireless standards do not exhibit as good energy-efficiency as is required by near-field IoT applications [96]. These factors necessitate the emergence of the transceivers at the MM-Wave band for this application and the use of the AoCs, therefore, will be very attractive candidates for such systems. One such transceiver has been designed in [96] at V-band which reinforces the idea of using MM-Wave band for the near-field IoT applications.

2) CHALLENGES AND FUTURE DIRECTIONS

- **Need for antenna miniaturization techniques:** A variety of IoT systems need to operate at lower frequencies, i.e. lower than the MM-Wave bands [184]–[193]. The outcome of a low operating frequency is the large antenna size which is highly undesired for IoT applications. This requires the use of novel antenna miniaturization techniques to ensure a small form-factor for the realization of the AoCs at bands lower than the MM-Wave. Exploring novel miniaturization techniques can be one of the promising future areas.
- **Need for efficient AoCs:** Pertinent and low-cost AoC efficiency enhancement strategies need to be employed to compensate for the performance degradation challenges associated with the AoCs for IoT applications when designed in Si-based technologies, otherwise the efficiency of such systems will be very low. For instance, a 1.46 GHz CMOS transmitter has been designed for IoT applications with diploe AoC in [133]. The radiation efficiency of AoC is just 0.6 %, which is very low. Such low efficiency for the AoCs is not adequate for the IoT applications, thus making the AoCs efficiency enhancement methods one of the hot future domains.

In addition to above, the migration of UHF RFID towards MM-Wave is subject to few challenges. The biggest issue is smaller reading distances due to higher propagation losses at MM-Wave frequencies [183]. This poses a challenge to AoC's design with respect to the performance. This also pushes the need for innovative performance enhancement methods for the AoCs.

C. REPLACEMENT OF THE WIRED INTERCONNECTS WITH THE WIRELESS INTERCONNECTS

The traditional metallic interconnects used for various applications such as chip-to-chip, inter-chip communication and networks-on-chip are unable to meet the demands of future high throughput communication applications because of severe limitations on the delay, power, area and bandwidth [194]. This pushes the need for alternative solutions. One of the most promising solutions is to replace the wired interconnects with the wireless interconnects which are capable of overcoming all these constraints because of the use of Si technologies which are the most attractive choice for this application because of their obvious advantages. This makes the AoC an extremely auspicious candidate for this application. In addition, the AoC can play a significant role to mitigate the delay problem caused by the long bond wires, metallic connects and parasitic [195] used in the conventional wired interconnect based systems. The pictorial representation of the wired vs. wireless interconnects using the AoCs is shown in Figure 10 which clearly highlights the advantages of AoCs based wireless interconnects over the wired interconnects such as the smaller chip-area, lower cost and lesser complex packaging. However, the packaging in horizontal and vertical stacked configurations in AoCs give rise to several severe issues such as front and backside radiations that may affect the overall system performance [196]. The quilt packaging in AoCs, on the other hand, mitigates the issues with conventional packaging style, enable direct radiation into the air, and reduce path loss [197]. In addition, the choice of materials in packaging, technologies, and interconnection mechanisms between radio die and antenna are the key considerations for the AoCs' packaging. A complete detail of the packaging issues can be found in [196], [197]. The details of few important practical applications for which AoC based wireless interconnects are suitable are given below.

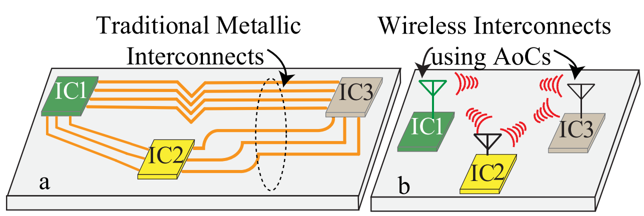

FIGURE 10. Conventional metallic vs. (b) wireless interconnects with the help of AoCs: a pictorial representation.

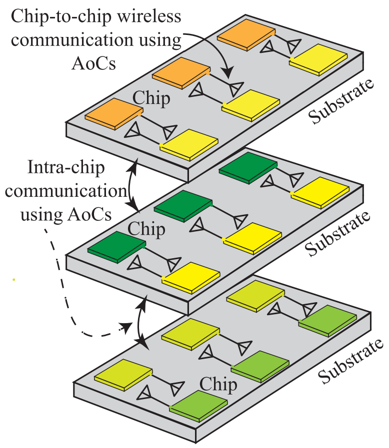

FIGURE 11. Conceptual representation of intra/inter-chip wireless communication: the chips communicate wirelessly with the help of miniaturized AoCs.

1) INTRA AND INTER-CHIP WIRELESS COMMUNICATION AND AoCs

- **Potentials:** The most important candidate for the AoCs based wireless interconnects is inter-chip and intra-chip wireless communication which has got substantial attention nowadays. The Si-based technologies are favorable for, both the transceiver design and the AoCs, for such systems because of their low-profile, low-power, low-cost, high integration and excellent high-frequency performance-based benefits. A graphical representation of the inter-chip and intra-chip wireless communication using the AoCs concept is shown in Figure 11 where various miniaturized AoCs based chips are performing inter-chip and intra-chip wireless communication. One possible future direction can be increase the operating frequency to MM-Wave for low profile and high performance systems.
- **Challenges and Future Directions:** The practical realization of the AoCs for this application exerts several challenges too. First, their performance is usually not at a level that is required for this application. The problem gets aggravated at the MM-Wave band due to an enhanced free-space loss [194]. Therefore, innovative solutions are needed to enhance their performance. The performance enhancement methods mentioned for 5G AoCs in section III (A (2)) can be utilized for inter and intra-chip wireless communication too. Second, there is sometimes a need to design such AoCs for the low-frequency operations, which in turn means an increased chip-size and the cost of the overall system. This requires the use of antenna miniaturization methods. The exploration of the solutions for both of these problems can be an excellent future research domain.

2) WIRELESS CLOCK DISTRIBUTION AND AoCs

- **Potentials:** Another recently renowned application is the wireless distribution of the clock to the digital ICs such as the microprocessors. Compared to all other clock delivery methods, the method of the AoCs based wireless clock delivery promises various advantages such as the subsidized delay, reduced noise, and hassle-free system packaging because of the elimination of the complex wired interconnects [132], thus making this one of the attractive future research areas. In addition, it mitigates the dispersion, clock skew, and jitter issues associated with conventional clock distribution methods [198]. The off-chip antennas based clock distribution system presented in [198] using 130 nm CMOS process demonstrates that wireless clock distribution not only subsidizes jitter, but also saves significant chip area and power. The AoCs based wireless clock distribution systems can significantly improve these advantages. Such a clock synchronization system using a fully integrated picosecond pulse receiver with a planar inverted-cone AoC is proposed in [199] in 65 nm CMOS process, which receives the pulses centered at 80 GHz. The measurement shows an RMS jitter value of 0.29 ps which is significantly low in comparison with other systems, thus demonstrating the potential of the AoCs for this application. This is further endorsed by the low value of the random jitter, i.e. 4.87 ps of the pulse centered at 3GHz, for the AoCs based single-chip ultra-wide band receiver for wireless interconnects [200]. The concept is illustrated in Figure 12 which shows that one AoC (labelled as TX) is being utilized as a transmitter antenna which is responsible for providing the clock wirelessly at all intended locations. The locations where there is a need of the clock are being occupied by the receiving AoCs (labelled as RX) which wirelessly receive the clock from the transmitter AoC.
- **Challenges and Future Directions:** Few such already designed systems using the AoCs reveal that the design of the AoCs for this application is subject to the serious challenges which need to be overcome. For example, the method proposed in [132] faces limitations in terms of the AoC's lower gain, which drastically decreases the range of the clock delivery system. This dictates the use of high-performance AoCs which is a serious challenge. Moreover, scaling up the operating frequency of the system can be a good solution to the increase in the gain [132] as well as a small form-factor of the antenna. It is, thus, extremely advantageous to design such systems at MM-Wave frequencies.

3) WIRELESS NETWORK-ON-CHIP (WNoC) AND AoCS

- **Potentials:** Network-on-Chips (NoCs) are central to the modern embedded cores and multiprocessor systems viable of a variety of domains and applications such as medical, consumer multimedia, image-processing, defence sector [195], artificial intelligence, scientific and multimedia applications [84], etc. Recently, the WNoC has emerged as a promising alternative for

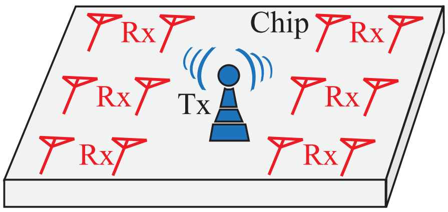

FIGURE 12. A conceptual representation of the wireless clock distribution to the microprocessors using AoCs. Rx = Receiving AoC and Tx = Transmitting AoC.

the conventional metallic interconnects based NoC and has been readily accepted to mitigate the large delay and high power dissipation issues offered by the NoC [195], [201]–[206]. The WNoCs are also intended to promise several other advantages such as the lower complexity, compactness, enhanced efficiency, high performance, re-configurability [207], and routing flexibility [84]. Wireless transceiver and antenna are two core sections of such systems. The set of above-mentioned requirements can best be achieved by designing these two sections using Si-based technologies and thus the use of the AoC is highly promising. Few such systems based on the AoCs have already been proposed [84], [112] which are also enlisted in Table 1, and 3 and demonstrate the suitability of the AoCs for this application. Besides these, one AoC based WNoC has been designed in [84] at k-band (26-40 GHz). One possible future direction can be to increase the operating frequency of this system to upper MM-Wave in order to achieve a further low-profile and high-performance system.

- **Challenges and Future Directions:** Several issues need to be mitigated for a successful design of the AoC for WNoC application. It is envisioned that the MM-Wave will be the enabling band for such WNoCs [201], [203], [204], [206]. However, shrinking the size of the AoC will be a tough challenge for the WNoCs where the operating frequency is lower than MM-Wave. Consequently, novel antenna miniaturization techniques need to be applied. For the applications where there is a need of the concurrent wireless interconnects to enhance the performance, the AoCs need to be directional in order to thwart the interference issues between different interconnects communicating at the same time [201]. The design of the directional AoCs at the MM-Wave band and their proper configuration and coupling for interference avoidance is not trivial task because AoCs are closely placed to ensure low-profile of the overall system.

4) 3-D WIRELESS NETWORK-ON-CHIP (3-D WNoC) AND AoCS

- **Potentials:** A sub-domain in this regard is 3-D WNoCs for which a growing trend is witnessed recently [208]. 3-D WNoCs are preferred over the conventional WNoCs in order to enhance the communication speed and data-rate and reduce the overall profile of the network. 3-D WNoCs usually need wireless interconnects to achieve a better energy efficiency [208]. The AoC is a superior candidate for this application as it addresses the size, delay, and energy limitations posed by 3-D WNoCs systems whereas the off-chip antennas are unable to do so.
- **Challenges and Future Directions:** In 3-D WNoCs, multiple AoCs are placed side by side to save the overall size of the network. These closely spaced AoCs are at a higher risk of triggering the coupling and interference issues for the network and AoCs. An appropriate interference-free mechanism needs to be applied for the solution of this issue. One useful way to mitigate this issue is to ensure the avoidance of all the other wireless links, i.e. the links which are not intended to perform the wireless interconnects function between these closely integrated AoCs. In addition, performing structural modification of the antenna design in AoC can reduce the coupling and interference issues. For example, reducing surface wave excitations in microstrip patch antenna using proper design of circular ring radius can reduce coupling [209]. Also, introduction of coupling paths between resonators can also reduce coupling [210]. Similarly, use of multimode antenna [211], EBG structures [212], dielectric grooving beneath the radiating element [213], incorporation of resonant slits [210], and Artificial Magnetic Materials (AMMs) [214] have been reported to mitigate coupling between AoCs. Moreover, the use of differential antennas, guard rings, vias fencing, and air cavity can also reduce EM coupling issue [196]. Nonetheless, there is a dire need for the novel solutions to this grave issue and based on this, it has become one of the appealing future research domains.

5) THE ELIMINATION OF SIGNAL WIRES FOR HOME BASED ELECTRONICS USING AoCS

- **Potentials:** Home electronics appliances use signal wires. The management of these wires is often quite complex. To make such appliances compact and the management of signal wires hassle-free, these wires can be replaced with high data-rate 60 GHz wireless communication interconnects since 60 GHz wireless communication is suitable for short-range due to high attenuation characteristics. Thus, a wireless communication system can be made much miniaturized because of the use of the AoCs [24]. Likewise, emerging ultra-short distance wireless interconnects (< 5 mm) [83] are also a good candidate for the use of the AoCs.
- **Challenges and Future Directions:** The range of both, the 60 GHz wireless communication interconnects based system and ultra-short distance wireless interconnects based system, is a critical factor in determining the performance of both of the above-mentioned applications and thus the efficiency of the AoCs for these

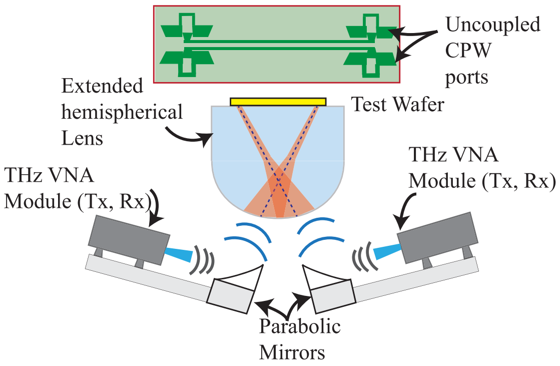

FIGURE 13. The MM-Wave and THz on-wafer, non-contact probe testing setup using AoCs [100].

applications should be high for a better range, which is difficult to achieve with the Si technologies. This drives the need for the use of performance enhancement methods for such AoCs.

D. CHARACTERIZATION OF ICs, DEVICES, AND ANTENNAS

Recently, two growing trends have been witnessed in terms of the ICs and antennas' measurement with the help of the AoCs. First, the use of the AoCs has been demonstrated for the mitigation of the several limitations posed by the traditional measurement setups of the ICs. Second, novel setups for the contact-less testing of the ICs and the antennas have been proposed which are either capable of alleviating the constraints of the conventional measurement setups or enable on-the-air testing. In the first case, the AoCs are an integral part of the measurement setup. In the second case, the use of AoCs can not only enhance the performance of the setups significantly, but also create tremendous opportunities for the novel measurement setups for various emerging applications. The detail is provided below.

1) NOVEL MEASUREMENT SETUPS FOR ICs USING AoCs FOR THE MITIGATION OF CONSTRAINTS POSED BY THE CONVENTIONAL SETUPS: POTENTIALS, CHALLENGES, AND FUTURE DIRECTIONS

- **On-chip baluntennas for the characterization of MM-Wave ICs:** In [100], an innovative on-chip baluntennas have been demonstrated with the help of novel double slot on-chip, lens integrated antennas for the on-wafer characterization of non-contact differential mode MM-Wave ICs and devices in the H-band (220-325 GHz). These measuring baluntennas mitigate the characterization limitations associated with the pure mode vector network analyser and balun integrated probes. A few of such limitations include the high cost and low reliability of the probes, the tough requirement of physical contact of the ICs with the wafer, and lack of the equipment and interconnects required for the testing. The setup is shown in Figure 13 where two antennas are manufactured at the input and output of the measuring device and the test signals are applied and received to the wafer without any physical contact. On-wafer testing of a high-electron-mobility-transistor (HEMT) was successfully performed using this setup. The frequency of these baluntennas can be extended to THz region because of their quasi-optical nature. In addition, one promising future idea is to come up with similar measurement setups for other frequency bands for the achievement of remarkable benefits associated with this setup.

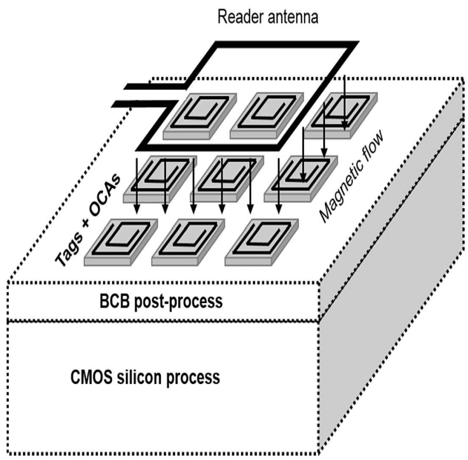

FIGURE 14. Wafer Level testing method proposed in [127] with the use of the AoC.

- **RFID and AoCs based ICs measurement setup:** In [127], a novel method has been proposed at 965 MHz with the help of RFID and an array of post-processed coil AoCs, which empowers a contact-less measurement of the ICs at the wafer level. The method is more economical than the conventional I/O pads based testing of the large ICs because of its small chip-area consumption and low-cost post-processing of the AoCs. The schematic of the test setup is shown in Figure 14, where the inductive coupling with the PCB reader antenna has been obtained with the help of the post-processed, high-quality near-field coil AoC based array, fabricated on the Si wafer under test. The AoCs' post-processing has been done on the standard CMOS wafer. By using a 27-dBm standard RFID reader, the testing of a tag array has been performed successfully achieving a reading range of up to 2.5 mm. From future prospects, there is a dire need of extending this concept for the measurement of other similar ICs. Moreover, a good future idea is to scale up the frequency of this method and make it viable for MM-Wave band testing by using innovative techniques. In addition, the quality factor of the coil AoC of this setup, which is only more than 20, can be enhanced to achieve better performance and reading range using post-processing method for the AoC.

2) INNOVATIVE SETUPS FOR THE CONTACTLESS MEASUREMENT OF ICs, ANTENNAS, AND AoCS

- **Wireless power transfer based antenna testing setup:** In [215], an innovative method for testing of

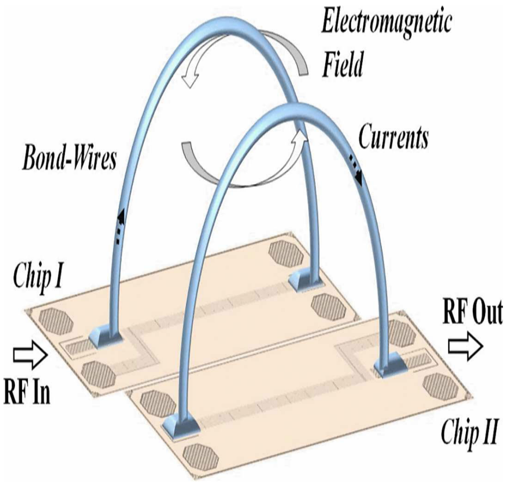

FIGURE 15. The novel method for chip-to-chip communication using coil antennas at 200 GHz for wafer testing during the ICs fabrication [215].

wafers/chips when they are still in the fabrication phase is proposed at 200 GHz. The method utilizes the wireless power transfer method for enabling the wireless communication between two physically spaced chips. The conventional physical contact based testing of such chips presents various serious problems such as the inductive and capacitive parasitics introduced by the bond-wires which are an essential part of such measurement process. These parasitics make the de-embedding of the ICs very tough during the measurement process with an outcome of inaccurate measurements. The proposed method is an effective solution to this challenge. In this method, the wireless interface or chip-to-chip wireless communication is ensured by the use of two off-chip bond-wire antennas at the two chips as shown in Figure 15. The proposed technique is compatible with the Si processes. This makes the use of the AoC very promising for this setup from future's perspective as all the advantages associated with the AoCs will make this method more efficacious. Moreover, the efforts are also needed to propose similar methods for other MM-Wave and THz region IC's characterization with the help of other types of innovative AoCs.

- **Unmanned aerial vehicles based antenna measurement setups:** Recently, a few UAVs based measurement setups have been proposed for the characterization of the off-chip antennas. In [216], the authors have proposed a method for the radiation pattern measurement of Very-High-Frequency (VHF) and Ultra-High-Frequency (UHF) off-chip antennas and antenna arrays by mounting a test source on a micro UAV. The system is shown in Figure 16 where a radio test source, consisting of a dipole antenna and an RF generator, has been mounted on the UAV. The system is especially suitable for the testing of the ground-based antennas for making astronomical observations.

  Another UAV based radiation pattern measurement setup, characterized by low-cost and better accuracy, compared to other such methods, has been presented in [217]. The main components of setup include: (i) a UAV equipped with the power detector, (ii) a UAV controller that has been implemented by a 433 MHz radio transmitter and receiver to avoid the interference issue with the other systems, (iii) a probe printed monopole antenna, (iv) real-time kinematic (RTK) beacon onboard, and (v) a WiFi antenna which is a part of the wireless local area network (WLAN) in order to ensure wireless communication with the ground station (laptop), UAV and a RTK beacon.

  Yet another similar set up has been presented in [177] for MM-Wave 5G based off-chip antennas. The major components of setup include: (i) a UAV, (ii) on-board monopole antenna that is connected to a power detector, (iii) a couple of RTK beacon modules, one functioning as a rover station and second as a base station system, (iv) RF receiver at 433 MHz, (v) a WLAN based communication system in order to enable wireless communication among UAV, (vi) RTK beacon and ground station, and (vii) a global navigation satellite system (GNSS) which tells the positioning of the system. The data achieved with this setup are further post-processed to assess the radiation pattern of the antenna. The setup is capable of measuring the antennas up-to 25 GHz.

  These UAVs based antenna setups are although less accurate, but they provide a real-time measurement as well as the information about the propagation impacts on the measurement results, i.e. how do the ever-varying environmental and propagation factors affect the measurement results? One potential future research idea is to validate if the similar measurement set up is also feasible for the measurement of the AoCs, especially at MM-Wave.

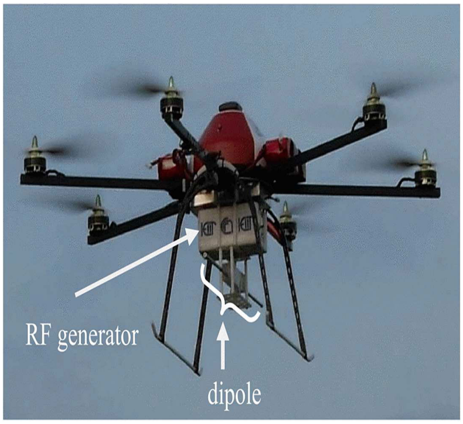

FIGURE 16. UAV based antenna radiation pattern measurement setup [216].

E. WIRELESS DEVICES FOR BIOMEDICAL APPLICATIONS

1) POTENTIALS

Because of unparalleled progress in biomedical technology in recent years, implantable biomedical devices have got a

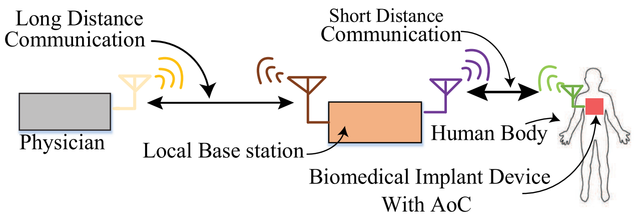

FIGURE 17. **Illustration of implantable biomedical device for patient's remote health monitoring with the help of AoC. Although one implant device has been shown here for the sake of simplicity, a large number of such devices will be inserted in the body to collect a variety of pathological and physiological parameters.**

remarkable prominence as a core part of the personalized health care system. Embedded in the human body, these devices wirelessly send the information about the pathological and physiological variations in the body tissues and thus help in timely diagnosis, monitoring, and treatment of remotely located patients. The working of a common wireless monitoring system is shown in Figure 17 where the AoC based implant device sends the pathological and physiological information wirelessly to the local base station, which then transmits this information wirelessly to a physician for the examination and diagnosis. It is a revolutionary step towards the provision of the best quality medical services to the ever-growing population of the world where traditional medical facilities and services will become inadequate. Moreover, it is a far better method than the orthodox method of external monitoring of the body tissues in terms of fidelity, precision, and patient's comfort level [218], [219]. These devices are feasible for a variety of tasks and applications such as glucose monitoring, pacemakers, intracranial pressure monitoring, brain-related functions monitoring, heart monitoring, respiratory system monitoring, transplants monitoring [218], [219], and wireless capsule endoscopy [220].

The realization of these wireless devices is impossible without accomplishing a certain set of requirements. First, they need to be highly miniaturized. Second, they must be very economical else their use becomes futile. Third, the use of the battery is not practicable for these devices because of the incessant need for battery replacement. Thus, they need to harvest the power from other sources. One possible solution is RF energy harvesting. Because of the scarcity of the energy available from other sources such as RF energy, these devices need to consume ultra-low power. Fourth, their performance should be insensitive to the impacts of human tissues.

Among available technology options, the use of Si technologies (CMOS, SiGe BiCMOS, SOI-CMOS) for these devices is an attractive choice to accomplish these requirements because of their low power, low-profile, and low-cost benefits. In comparison with the large off-chip antennas, the use of the AoC for such devices becomes an attractive choice because of the synchronization of AoCs' advantages with the set of requirements needed for these wireless health devices and systems. In fact, the Si technology based AoCs have already demonstrated their potential for such systems because of these advantages. For instance, the authors have proposed a coil AoC based inductively-coupled WPT receiver using 130 nm CMOS technology in [221] which shows a better peak WPT efficiency (0.8 % through 7.5 mm of bovine muscle and 2.5 mm of air) for biological media than WPT systems based on off-chip coils. The proposed system is compact, achieves a peak quality factor of 11.05 for the on-chip coil, and capable of delivering millimeters of power to biomedical implants without causing any damage to the biological tissues in terms of power density and EM exposures. In addition, the first fully integrated WPT system with on-chip coil at 144 MHz using 180 nm SOI CMOS for mm-size implants [222] shows a measured WPT effieincy of 2 % at 160- μW load which increases to 5 % at 700-μW load. Moreover, the dual-mode RF energy harvesting system of [223] with on-chip coil using 180 nm SOI CMOS for mm-sized biomedical implants shows state-of-the-art performance in terms of miniaturization, power deliver mode with continuous and duty-cycled modes, and peak conversion efficiency. In addition, the system exhibits immunity to the variations of wireless link parameters and loading.

2) CHALLENGES, FEW GUIDELINES FOR THE SOLUTIONS, AND FUTURE DIRECTIONS

- **To achieve the AoC's miniaturization at low frequencies:** The miniaturization of the AoC is an essential requirement for this application. However, it is a real challenge to accomplish this requirement. The Federal Communication Commission (FCC) has allocated a standard band of 401-406 MHz for medical implant communication. A majority of the biomedical devices and systems operate in this band. For instance, one such system, based on the off-chip antennas, has been designed at 402 MHz in [218] and one CMOS based transmitter has been designed in [224] at 403 MHz. Besides this band, other low-frequency bands are also popular for biotelemetry application. For instance, one such off-chip multi-band antenna designed in [219] operates at 2.4 GHz and 4-10.6 GHz and another off-chip antenna designed in [225] works at 2.4 GHz. Also, another off-chip antenna designed in [226] operates at 900 MHz, 1800 MHz and Bluetooth-Low-Energy band. Likewise, the off-chip antenna of [220] operates from 0.721 GHz to 1.705 GHz and the antenna proposed in [227] works at 915 MHz ISM band. The CMOS on chip-coil based system for biomedical implants proposed in [222] operates at 144 MHz. The CMOS based WPT sytem with on-chip coil [221] works at 100-250 MHz to ensure a peak efficiency. The on-chip coil [223] based RF harvesting system, implemented in 180 nm SOI CMOS, has an operating frequency of 434 MHz. Designing such devices at MM-Wave bands can be a viable solution for this problem as MM-Wave promises high data rates and large bandwidth. The biomedical implant devices are an important part of the emerging internet of Bio-Nano Things paradigm [228]–[230]

and THz band is considered the most favorable choice in this regard.

- **The need for an AoC insensitive to the body tissues and characterization challenges:** The performance of biomedical implant device based antennas often degrades abysmally within the body because of the effects of the dielectric properties of the biological tissues [218] as evidenced by the AoC designed in [231] where its performance severely deteriorates with the integration inside the human body. The fact that the dielectric properties of the different body tissues are frequency dependent worsens the problem [226]. In addition, the biological tissues have the potential to vary the resonance frequency of the in-body antenna [232]. Keeping in view the already degraded performance of AoC in Si technologies, these problems impose the use of novel performance enhancement methods for the AoCs which must not cause an increase in the size and cost of the AoC. Another potential future trend is the precise modelling and effects of biological tissues on AoC's performance for biomedical implant.
The testing of such miniaturized AoCs is an extremely tough job [51] and raises a need for innovative low-cost measurement setups and techniques. One such novel setup has been proposed in [231] for the testing of the implant AoCs in a frequency range of 1-8 GHz, but it is limited in its measurement capabilities since it is unable to measure the gain and radiation pattern of the AoC [226]. The methods and techniques discussed in [51] can be useful in this regard.
- **The need for an efficient AoC to avoid high specific absorption rate:** The Specific Absorption Rate (SAR) [218], [219], [233] or implantable medium loss [224] should be as low as possible. The high medium loss or SAR means a poor performance which is usually the case for already designed systems using the off-chip antennas. For instance, the efficiency of a CMOS based transmitter of one such system designed in [224] is just 0.015 %, whereas it is just 0.8 % for CMOS based systems proposed in [222]. In addition, the efficiency of the fully-integrated RF energy harvesting system of [223] with on-chip coil is only 0.68 %. This puts an extra challenge for the AoC since it dictates its geometry, placement, and configuration in order to avoid a high medium loss. In addition, this reinforces the need for a highly efficient AoC for this application.
- **AoCs robustness and EMI issues:** The antenna should be robust enough for a long term use inside the body as its replacement is highly undesired because of the need for the surgery and complex procedures involved [223], [226]. This exerts a grave challenge for tiny AoC due to its fragile nature. The solution to this challenge is essential for the successful realization of these devices. Further, special packaging mechanism may be needed to protect the AoCs from any damages.
For wirelessly-powered biomedical implants, the creation of an EMI problem escalate the loss [233] and degrade the performance of the AoC abysmally [220]. The mitigation of EMI is a daunting task to achieve for the AoCs since these parameters could face a trade-off with other parameters of the AoCs. This problem can be overcome by adopting the EMI mitigation techniques. One method to mitigate this effect is to place the AoC far away from the remaining part of the RF front-end section. The disadvantage of this is the larger size, increased cost, and effect on matching of the AoC because of nearby inductors [234]. One of the effective methods to eradicate this effect is to place the inductors and AoC in such a way that opposite direction of currents in both (inductors and AoC) cancel the electromagnetic field and abates the EMI coupling effect [1]. The EMI issue can also be mitigated by appropriately changing the inductor's direction, isolating on-chip ground sharing for the AoC inductor [234], and avoiding the long connection lines.
- **The need for dual-band AoCs:** There is a dire need of a single antenna for both, the energy harvesting circuit and the data communication circuit for this application in order to ensure system's miniaturization [232]. This requires the antenna to be dual-band; one band for the energy harvesting function and other for the data transfer function. This is a grave challenge as the design of a single dual-band AoC which can display better performance at both the operating bands is an extremely difficult task [235]. Table 1-4 confirm that already designed dual-band AoCs are very few in the literature.

F. RF ENERGY HARVESTING AND WIRELESS POWER TRANSFER

There is a wide range of emerging applications and systems which cannot be made functional without wireless transfer of power using RF energy harvesting. The battery or traditional power source is either not available or its use is not feasible due to several limitations [236], [237]. Some of these applications include WSNs [81], [238], [239], biomedical implant devices [133], IoT wireless transceivers [133], [240]–[242], mobile edge computing and communication networks [238], micro aerial vehicles such as micro drones [243]–[246], charging of mobile phones and laptops, and household robots [247], small aircrafts [248], electric vehicles [249], [250], charging of cameras for wildlife applications [251], high power applications [252], and smart computer numerical control [253]. There are three different methods which are normally used for the WPT. These include magnetically coupled resonant WPT [254], Electromagnetic Waves/RF energy WPT, and inductive coupling WPT [240]. The RF-WPT is used for the far-field WPT whereas the other two methods are suitable for the near-field WPT [240]. Two application scenarios of WPT are shown in Figure 18 which shows the mobile vs. immobile WPT device for the charging of the different devices. In Figure 18 (a), a mobile charging device has been utilized for wireless power transfer to the fixed cameras which are intended to monitor the wildlife environment. In contrary, a fixed charging device has been used in Figure 18 (b) to charge up the mobile devices in an office environment.

1) POTENTIALS

- **Ensure low power, low cost and miniaturized WPT based systems:** It is essential for the WPT based systems to meet certain requirements else their realization becomes impossible. First, they need to be low cost and robust, otherwise their use as a replacement of a battery or power source is futile [237], [255]. Second, they need to be low-profile as a large majority of the systems and applications which employ WPT face space constraints. Third, they must be energy-efficient in order to meet the demands of the driving systems. The best way to achieve all these requirements is to use Si-based technologies (Table 4) for the design of such systems and the use of the AoC, therefore, becomes a promising choice.
- **Eliminate the need for impedance matching network:** There is another distinctive reason for the use of the AoCs for the RF-WPT systems. The rectifier and antenna are two main components of RF-WPT system [244]. The proper matching between the antenna and the rectifier circuit is of vital importance to the overall efficiency of the system [256]. The impedance of the antenna depends on the incoming EM waves for such systems; this pushes the need for an adaptive impedance matching network which is an extremely challenging task. These problems can be solved with the use of the AoC where there is absolutely no need for an impedance matching network. This concept is illustrated in Figure 19. The use of AoC becomes more advantageous for the WPT systems which employ the rectifier arrays [244]–[248] as well as for the systems which use multiple antennas to increase the efficiency of the system.
- **Suitable for antenna array based WPT systems for efficiency enhancement:** Another distinct advantage of the AoCs' use for a WPT based system to increase its efficiency instead of using off-chip antenna arrays to form the switched/steered-beam which occupy large chip area [240], [242], [243], [251], [253], [257]–[259]. The use of the AoC based array not only bestows a reasonable amount of gain, but also occupies small chip-area. Another benefit of this approach is its flexibility, i.e. it permits the increase in the array elements as per the requirements for the efficiency raise without a considerable rise in the chip area and cost.
- **Well-suited for novel efficiency enhancement methods proposed for WPT systems:** Recently, few innovative methods for the enhancement of the efficiency of WPT systems, based on off-chip antennas, have been proposed. The off-chip antennas of these systems can be replaced by the AoC either to mitigate the efficiency limitations of these systems or to achieve extra benefits. One novel solution for low efficiency problem has been presented in [238] which uses a UAV based WPT system equipped with a directional off-chip antenna which makes use of the UAV's controlled mobility feature to change its location in order to vary the distance from the two different energy receiving systems stationed on the ground. The AoC can successfully replace the off-chip antenna of this system as the system needs a moderate amount of gain due to the mobility of the UAV. The AoC also provides additional benefits of the compactness and low-cost over off-chip antenna. Another solution has been proposed in [255] which uses distributed network equipped with a central processor and a set of distributed off-chip antennas, both playing the role of a base station. A similar distributed antenna based WPT approach has been presented in [260] as well. The multiplicity of the antennas substantially increases the overall chip area and cost of both of these systems. The AoCs are capable of overcoming these issues and thus can successfully replace the off-chip antennas of these systems.

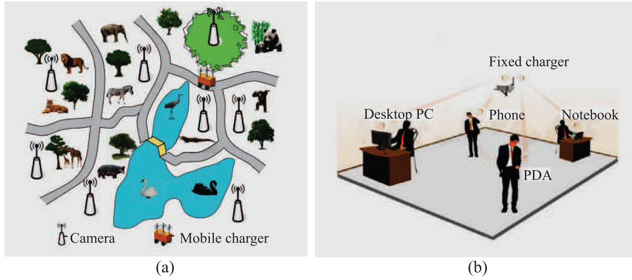

FIGURE 18. Two application scenarios of WPT: (a) in wildlife refuge monitoring scenario where a mobile charging device has been used for the fixed cameras; (b) an office environment where an immobile charger charges the mobile devices [251].

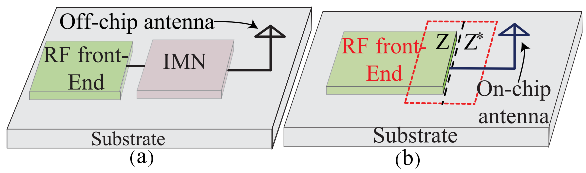

FIGURE 19. Comparison of off-chip and on-chip antennas w.r.t impedance matching networks (IMN). The AoC does not require any IMN. Its impedance can be conjugally matched with the impedance of RF front-end section by the antenna-transceiver co-design approach.

2) CHALLENGES, MITIGATION METHODS, AND FUTURE DIRECTIONS

- **The need for highly efficient AoCs:** The most serious issue of the WPT and RF energy harvesting systems and antennas is their low energy efficiency [237], [242]. For example, the efficiency of the wirelessly-powered temperature sensor designed in [81] is only 1.8 % and the radiation efficiency of a 7 GHz in [133] is just 13 %. This dictates the use of performance enhancement methods for such AoCs else the achievable efficiency will not be adequate.

It is highly desired to achieve a higher range WPT system which is extremely difficult to accomplish as the WPT system based transmitter is fixed and the power decays with the inverse of the square of the distance [238]. This again needs a high-performance AoC and innovative performance enhancement methods for the achievement of this goal such as coupled resonant based WPT [247]. Few antenna configurations can provide better efficiency over the others for WPT systems. One innovative method has also been presented in [249] for off-chip coil antennas based inductive WPT. In this method, the authors have modelled the WPT system as a linear circuit and expressed its input-output relationship in the form of a small number of unknown parameters which can be considered as gains and transimpedances. The model is then verified by a set of experiments and it is demonstrated that this model is better than other such methods in terms of efficiency enhancement of WPT systems. As future work, the viability of the above-mentioned methods needs to be validated for the AoC too. In addition, a couple of innovative efficiency enhancement methods, other than these, for WPT systems have been proposed recently based on off-chip antennas (Section III (F(1))). These methods can also be designed with the help of the AoCs instead of the off-chip antennas to obtain added advantages as future research work.

- **The requirement of efficient omni-directional AoCs:** One of the important requirements for several applications is that the single WPT system should be capable of simultaneously powering multiple devices [254] (Figure 17). This poses another challenge to the AoCs since the receiving devices are generally at different locations due to the environmental limitations and it is extremely challenging to design an AoC which can effectively radiate in all directions. One potential solution is the use of the beam-forming mechanism with the help of AoC arrays as explained in the advantages section. However, the beam-forming comes with its own complexities such as the need for addressing proper coupling between different antenna elements.
- **The need for AoC's miniaturization at low frequencies:** For RF energy harvesting, it is a common practice to design the harvesting circuits at frequencies where a reasonable amount of energy is available. Otherwise, the efficiency of the system will be low because of the paucity of the available RF energy. Due to this reason, a large majority of such systems have been designed at the relatively lower side of the GHz frequency spectrum [227], [239], [243], [244], [248], [252], [261]–[263]. In addition, Table 4 shows that the already designed WPT systems based on the AoCs also operate at lower GHz frequencies. This makes the design of a low-profile AoC an extremely daunting task and hence pushes the need for novel antenna miniaturization methods. Another promising way to solve this issue is to design WPT systems at MM-Wave. One such WPT system based model has been proposed in [242] which asserts that the energy efficiency of MM-Wave based WPT is better than low-frequency systems. There is a dire need of implementing this system on circuit level using the AoCs in the future to assess its potential for a multitude of innovative applications. Besides high efficiency, large bandwidth and high data rates are the added advantages at MM-Wave bands.

G. WIRELESS SENSOR NETWORKS (WSNs)

1) POTENTIALS

A WSN consists of a plethora of different distributed sensor nodes and has many application such as smart homes, home care systems, surveillance, and automation [18], [19]. Besides other stringent requirements, an ultra-low power dissipation, small form-factor, and low cost are the key requirements for WSN based transceivers [17]–[20]. Moreover, several WSN applications such as wireless body area networks, wearable WSN and wireless medical telemetry need to harvest energy from the environment. In addition, the AoCs are highly promising to act as an antenna array for the WSN based RF energy harvesting circuits in order to enhance the energy efficiency of the energy harvesting circuits because of their low-profile and low-cost advantages. The detail of the very few already designed AoCs for the WSN application can be found in Table 1.

2) CHALLENGES, FEW GUIDELINES TO OVERCOME THE CHALLENGES, AND FUTURE DIRECTIONS

- **The need for AoC's miniaturization methods for low-frequency WSN applications:** The use of the AoC for MM-Wave based WSNs is conspicuously beneficial because of the antenna's small form-factor. However, there are several low GHz frequency bands such as, 2.4 GHz [20] and 4.8 GHz [17] are considered attractive for WSN applications. These bands pose a severe challenge for the AoC's design in terms of its miniaturization and novel antenna miniaturization methods is indispensable to ensure an overall smaller chip-size of the system.
- **The requirement for high-performance AoCs:** Several remotely located WSNs often require harvesting energy from the ambience as the use of the batteries or conventional power sources is not feasible. RF-based wireless energy transfer or harvesting is one of the best methods for this purpose and offers several benefits over the magnetic resonance and inductive coupling based methods. A few of these benefits include the potential of energizing a large number of sensor nodes, an ability to transmit information to the nodes, ensuring a small form-factor, and providing an opportunity for the use of MIMO techniques for the enhancement of energy efficiency. However, the decline in energy efficiency

with an increasing distance is a grave issue for this method due to a severe attenuation of EM waves [19]. This is validated by the example of a wirelessly powered temperature sensor of [81] where an energy efficiency of only 1.80 % has been obtained. Besides other means, one of the potential ways to enhance the energy efficiency of such systems is to use high-performance AoCs. This exerts a challenge to AoC design as the performance of AoC is generally low. One method to overcome this issue is the use of one of the performance enhancement techniques for the AoCs. The other way is the utilization of AoC based array for this purpose which also promises an insignificant increase in the chip area of the system.

H. WEARABLE ELECTRONICS

1) POTENTIALS

- **Ensure compact, cost-effective, low-weight and low power solutions:** Wearable devices have found a particular interest in recent days owing to their ubiquitous applications in a multitude of domains such as sports, health, navigation, textile, physical training, rescue services, military, space [264]–[272], etc. The design of electronic components for wearable applications poses several challenges and one of the most significant challenges is the design of the antennas. These antennas need to be either integrated within the human body or embedded inside the clothes. This integration dictates them to be low cost, low-profile, robust, reliable, low power, and lightweight, otherwise, they become ineffective for these applications [59, 234, 239]. These requirements make the use of the AoCs favorable for this application because of the provision of relevant advantages demanded by this application.
- **Suitable for MIMO array application for the mitigation of body impacts on wearable devices:** The performance of wearable antennas usually depletes in close proximity of the human body or inside the human body since the human body absorbs power from the antenna [267]. Moreover, the coupling between antennas and the human body causes serious issues and abysmally degrades the radiation characteristics of the antennas [274], [275]. In addition, the body movement badly degrades the antenna's performance because of the scattering, multipath fading, and shadowing effects. One effective solution to mitigate all of these problems is the use of MIMO based antenna arrays which provide flexibility to manage these issues by a judicious coupling among different array elements. One such off-chip antenna array has been proposed in [60] at V-band for wearable button applications. The added advantage of a MIMO based array is its ability to provide diversity performance for high data rate. Two diversity performance based of-chip antennas have been designed in [276] for wearable devices at 2.4 GHz WLAN band. However, one of the limitations of the MIMO approach is that the overall size of the system increases significantly due to the off-chip antennas. The use of the AoCs for such application is, thus, very promising as it solves the size issue with the added benefits of lower cost and low loss. Recently, a significant work has been done on the off-chip antennas for this application [60], [266]–[269], [276]–[281]; however, a very little work can be seen on the wearable AoCs. One AoC has been designed for wearable biomedical applications in [231], but this design shows that its performance degrades abysmally with its integration inside the human body. Also, gain and radiation patterns could not be measured accurately by the proposed setup [51].

2) CHALLENGES, SOME MITIGATION TECHNIQUES, AND FUTURE DIRECTIONS

- **Need mitigation methods to avoid body effects:** The radiation efficiency and the operating frequency of the wearable AoC should not be affected with the bending or the movement of the body parts which is usually a common occurrence for such applications [60], [273], [281], [282]. This is a serious challenge for such AoCs since they need special packaging mechanisms to protect them against these body actions. These packaging methods may then disturb the other parameters of the antenna which raise the need for their interdependence analysis and novel methods to offset their undesired interactions.
- **Require antenna miniaturization techniques at low frequencies:** A large majority of the off-chip antennas designed for this application operate at lower frequencies, i.e. microwave [283]. This poses, in one way, a grave challenge for the AoCs since their large size will make them infeasible for this application. This requires novel antenna miniaturization techniques for such AoCs. One such novel method is presented in [284] in the form of the Magnetoelectric off-chip antennas. The Nano-scale Magnetoelectric antennas which have been proposed recently takes into account the magnetic current for the generation of the EM waves from the antenna in contrary to conventional electric current. These antennas are 1-2 orders more compact than traditional off-chip antennas and also very suitable for wearable applications. However, nano-scale magnetoelectric technique has scalability and compatibility issues. One future research idea is to design magnetoelectric AoCs which will ensure their miniaturization at low frequencies. On the contrary, antenna having conjugate composite structures can be a promising candidate for realizing miniaturized antennas at low frequencies [285]. Other on-chip miniaturization techniques include: EBG loading [286], introduction of slots and notches [287], use of high permittivity substrate [288], and AMC loading [289], etc. The AoCs miniaturization challenge at low frequencies also creates a great research opportunity for the designers to design wearable AoCs at MM-Wave, which not only ensures

small size, but also promises a high data rate and large bandwidth advantages.

- **The need for multi-band AoCs:** A multiband operation is highly desired for this application to enable the multiple communication standards. Design of multi-band AoCs is a tough job as evidenced by Table 1, 2, 3 and 4 which show the scarcity of already designed multi-band AoCs. Recently, one tri-band AoC has been proposed in [125], but it is based on simulation work. From a future prospect, the challenge of multi-band AoC design can be overcome in three ways. First, few commercially available SiGe BiCMOS processes such as 130 nm SiGe BiCMOS now facilitate built in MEMS switches which can be used for the design of multi-band AoCs. Second, parasitic loading can be utilized for the design of multi-band AoCs. Third, the multi-band AoCs can also be designed with the use of on-chip switches as done by the authors in [91] for the design of a Q-band frequency re-configurable AoC.
- **Difficulty in modelling the human body effects on AoC's performance:** One way to reduce the impacts of the body on the antenna's performance is either by the careful placement of the antenna on its ground plane or by judiciously shaping the ground plane in accordance to antenna's electric and magnetic fields. Such effects cannot be taken care of during the antenna design cycle since the permittivity of the human body varies from person to person depending on the location of the antenna [282] and also with the frequency [290]. This dictates the need for the correct modelling of these effects during the AoC's design phase which is extremely difficult. In addition, the presence of these effects creates a grave challenge for the measurement of such AoCs because of their unpredictable nature, resulting in the inaccurate measurement results.

I. AUTOMOTIVE/VEHICLE INDUSTRY

The AoCs have also become a potential candidate for automotive applications. The detail of a couple of such emerging applications is given below.

1) THE CONNECTED/NETWORKED VEHICLES AND CARS

(i) **Potentials**

Today, the world is witnessing an astounding development in the connectivity of the vehicles and cars. The future features and functions of the connected vehicles such as cloud computing, a variety of sensors, multiple antennas for enabling the communication between the nodes inside and outside the vehicle, and the data networks inside the vehicle will reshape the vehicle industry. Nowadays, cars have more than 20 antennas to enable various applications, functions and communication standards such as the cellular, bluetooth, satellite, and multiple sensors inside the cars. The multiplicity of the antennas will put the car manufacturers in a real challenge with a primary question: how to integrate all the antennas inside the car in a compact and economical way [291]? The AoCs have the potential to solve this issue due to their miniaturized nature and low cost benefit.

(ii) **Challenges, Some Guidelines to overcome the Challenges, and Future Directions**

- **How to get a compact AoC at low frequency?** The connected cars of the future will still need several communication standards at lower frequencies besides communication applications at MM-Wave such as 5G. The size of the AoC for low-frequency standards will be larger because of the large wavelength which is undesired and there will be need for effective antenna miniaturization methods.
- **How to mitigate RF and EM interference issues?** Because of the presence of a large number of AoCs packaged closely to save the car space, EM and RF interference issues will get prevail which needs to be overcome efficiently. As a result, the proper shielding of each antenna will become an essential requirement [291] besides other mitigation techniques. A viable technique for the mitigation of the antenna interference issues has been presented in [148] which proposes a different design methodology for such antennas. Instead of designing antennas individually and integrating them later in the car, this design approach suggests that it is better to design all the antennas in a way that function together as a system at first and then integrate this single working antenna system inside the car.
- **The need for multi-band AoCs:** Each wireless communication standard and device of the connected cars will require different AoC because of the different operating frequency bands. These multiple AoCs will, consequently, occupy a significant car space. To solve this issue, one effective solution is the use of multi-band AoCs, however, the design of multiband AoCs is a tough task.

2) THE AUTONOMOUS VEHICLES/SELF DRIVING CARS (SDCs)

(i) **Potentials**

The dream of autonomous vehicles or SDCs will transform into a reality in the near future owing to the enormous progress in the field of wireless communication and the innovative developments in the domain of low-cost technologies. For a safe and reliable operation, these vehicles need to communicate wirelessly with the 3G, 4G, and 5G systems for the map and collection of other web-based information as well as with the other cars on the road for collision avoidance [292]. Besides other components and systems such as sensors, softwares [293], and radars [294]–[296], multiple number of antennas occupy a substantial space inside the SDCs. In order to save the space and cost of SDCs, the large off-chip antennas can be replaced by the miniaturized AoCs. In particular, the use of the AoCs (Table 1 and 2) is highly attractive for MM-Wave automotive radars, which are an essential part of the SDCs to perform the collision avoidance and location estimation functions.

(ii) **Challenges, Some Guidelines to overcome the Challenges and Future Directions**

- **The need for over-the-air testing of SDCs:** To maintain a secure and reliable function, over-the-air testing of the SDC based antennas is indispensable which aggravates the already tough task of measuring the AoCs. For instance, the testing of the GPS AoCs integrated inside the SDC is essential for its performance assessment in the complex practical environment since the SDCs usually operate in the complex environments and are at a higher risk of GPS communication blockade by the other vehicles on the road [293]. This calls for novel and cost-effective measurement solutions and methods for accurate and reliable characterization of such AoCs. Two miniaturized and low-cost test chambers, one reverberation and other anechoic chambers, for the over-the-air measurement of the SDCs, have been proposed in [292]. The reverberation chamber is capable of performing multipath testing of the SDCs in a rich isotropic multipath environment and the anechoic chamber can test the SDCs in a random-line of sight environment. There is a need for assessing the viability of these chambers for the AoC based SDCs as future work. In addition, the modelling which can perfectly mimic the practical complex environment similar to the SDC's one during the design phase of the AoCs is crucial for the design success. The AoCs measurement methods presented in [51] are also useful in this regard.
- **The need for proper coupling between MIMO AoC based array elements:** The performance of the SDCs is primarily contingent on the antenna performance, especially for the obstacle and collision avoidance. In this regard, the direction of arrival estimation is a critical requirement for such AoCs to enable the desired coverage. One of the best ways to do so is the use of MIMO based spatial diversity method [296], [297] because it permits the beam forming and beam refinement of the AoC based arrays according to the requirements. This not only favours the use of the AoC based arrays for this application because of their compact nature, but also offers a serious challenge in terms of proper placement, configuration, and coupling between different array elements, and the judicious alignment of the beams.
- **The size reduction low-frequency AoCs and design of multiband AoCs:** Because of the several communication standards working at low frequencies such as GPS, the size of the relevant AoCs will enlarge. To reduce the size, one promising way is to apply the novel antenna miniaturization methods.
  Because of the multiple standards at different frequencies and use of different antenna for each standard and application, it is highly desired to get multi-band AoCs for this application in order to ensure miniaturization. The design of multi-band AoCs presents serious challenges of their own.

J. UNMANNED AERIAL VEHICLES (UAVs)

The recent years have witnessed the unprecedented proliferation of UAVs or drones in a variety of diverse applications. Few of these applications and functions include WPT [238], IoT [243], [298], [299], target estimation [300], remote sensing [301], examining of inaccessible and dangerous places [302], weather monitoring [303], antenna characterization [177], [216], [217], aerial mapping [304], wildfire monitoring [305], crop growth monitoring [298], land monitoring [306], and detection of harmful EM fields [307]. This widespread use will require extensive efforts for the rapid developments of the UAVs in the future.

1) POTENTIALS

The UAV essentially needs antennas for communicating with the base station/controlling station and are required to send higher quality video/audio to the base station with great fidelity. Different types of communications are performed by the UAV such as GPS, telemetry, WiFi, and telecommand [302]. The antennas are obviously essential for all of these functions [308]. The antennas for the UAV need to be low weight, compact, low cost, modern fabrication techniques friendly, and compatible with the modern systems in terms of the integration [243]. The AoCs, thus, becomes a suitable candidate for this application. Given below is the detail of a few other reasons which make the use of the AoC very attractive for this application.

- **Ensure stable performance against thermal, electromagnetic, and mechanical factors:** The antennas for this application must have excellent aerodynamic features [309] and should exhibit superior performance stability, thermally, mechanically, and electromagnetically [300], [303]. Also, the antennas should not disturb the power management function of the UAV [302]. Furthermore, the antenna's performance should be insensitive to the ever-varying air resistance [310]. One of the best ways to achieve all these goals is to use a miniaturized antenna. Another benefit of a compact antenna is that it will have a minor impact on the flight performance of the UAV [309]. The AoC obviously becomes a strong choice for this application.
- **Suitable for antenna arrays for broader view and range of UAV:** In order to get a highly desired wider field of view for the UAV, the use of the antenna arrays is a promising solution [300], [308], [311], [312]. However, this benefit comes at the cost of the large

area consumption and thus high budget. The AoC based arrays can perfectly alleviate this challenge because of their small size and low-cost benefits.

In order to achieve a long range between the UAV and the controller/base station, the performance of the antenna should be high [314] which is difficult to achieve without the use of large antennas which, in turn, enhances the overall profile of the system. This trade-off can be overcome by using the AoCs where their performance can be enhanced with the application of performance enhancement techniques. The added benefit of this is that the AoC arrays can now be used for wireless range enhancement without a substantial increase in the system's chip-area.

- **Well-suited to small UAVs:** The small UAV puts a limit on the gain and bandwidth of the antenna due to its miniaturized and low-weight platform. This low-profile platform restricts the use of multiple antennas which are essential to perform different functions of UAV [301]. The use of large off-chip antenna array to enhance the gain is also not feasible. The use of the AoCs or AoC based arrays can single-handedly solve all above mentioned issues in one go since their small size makes the integration problem a straightforward task. Moreover, extra functionalities can be achieved without a significant increase in the profile of the platform of the small UAV. In addition, the micro or small UAVs often need wireless charging for the increase in their flight time as well as autonomy. They, thus, need a WPT system, as discussed in Section III (F(1)) of the paper.

2) CHALLENGES, FEW MITIGATION METHODS, AND FUTURE DIRECTIONS

- **WPT systems for micro UAVs:** Recently, Micro Aerial Vehicles (MAV) such as micro drones have attracted significant attention because of their multitude of applications in diverse domains [243]. The wireless charging of these drones is highly desired in order to increase their flight time and thus autonomy [245]. This requires a WPT system for which the use of the AoC is challenging (Section III (F)).
- **Large antenna size for low frequency functions of UAVs:** The operating frequency of a large number of UAV based antennas is low since their usual operating bands are High-Frequency, VHF, and UHF [301], [302], [308], [309], [314]–[316]. It is highly desired to have a compact AoC to avoid serious issues such as the interference with the nearby objects and a stable performance despite aerodynamics variations. The use of the AoC, thus, for this application necessitates the use of antenna miniaturization techniques. Another promising solution is to design such systems at MM-Wave [311] for high data rate and large bandwidth benefits which are vital requirements for many state-of-the-art applications using UAVs.
- **The need for multi-band AoCs:** It is highly beneficial to design multi-band antennas for the UAVs. For instance, one multi-band segmented loop off-chip antenna has been designed in [310] covering 1.57 GHz, 1.71-1.88 GHz, 1.85-1.99 GHz, 1.92-2.17 GHz, 2.3-2.4 GHz, 2.5-2.69 GHz, 2.4-2.485 GHz bands. One dual-band off-chip antenna has been proposed in [312] which operates in 2-5.9 GHz and 430-450 MHz bands. Another tri-band off-chip antenna has been presented in [316] working at 840.5-845 MHz, 1430-1444 MHz, and 2408-2440 MHz bands. However, this is a tough job to get the required performance at all the operating bands for the AoCs. The requirement of a single antenna with a directional response at one frequency and an Omni-directional response at other frequency is also very difficult to achieve with the help of the AOCs. This is often required for those UAVs where the directional response is needed for receiving high-quality images or videos from the remote locations and the Omni-directional response is required for receiving the data/report from the UAV [312]. Innovative solutions are required in this regard.

3) NOVEL APPLICATIONS BASED ON UAVs AND AoCS: POTENTIALS

A few innovative applications based on the UAVs have been proposed in recent days. This section endeavors to showcase these potentials and are provided below.

- **WPT systems equipped with UAV:** In [238], a UAV, equipped with a directional off-chip antenna, has been utilized for the design of an efficient WPT system, where UAV varies its distance dynamically from the energy receiving systems as per requirements. The mobility of the UAV relaxes the gain requirement of the antenna. Thus, the off-chip antenna of this system can be substituted by the AoC which is not only able to provide a moderate amount of gain, but also capable of reducing the cost and area of the system. Another such WPT system for a microdrone has been proposed in [245] at Ku-band using off-chip leaky wave antenna. This off-chip antenna can also be replaced with the AoC which will make this design more compact, low power, cost-effective and lightweight.
- **UAV system and location monitoring:** In [298], an amateur drone monitoring mechanism based on the off-chip antennas and with the help of a careful study of the wave propagation characteristics at different potential frequency bands has been proposed. The study shows that the 60 GHz band is more suitable for this type of drone monitoring system. The AoCs, thus, are very favourable for this system because of their added advantages over the off-chip antennas and opens up a novel research horizon.

  For the UAVs, one important requirement is to track the location of the flying UAV in order to get reliable

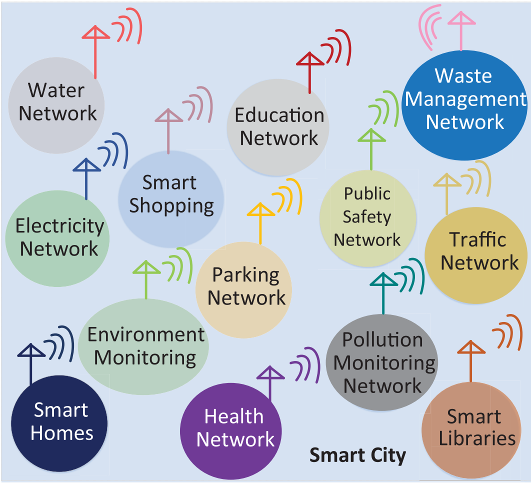

FIGURE 20. Pictorial representation of wireless networked based smart city concept. Each of the networks can use one or more than one AoC for wireless communication. However, only one AoC per network is shown here for the sake of simplicity. In addition, the AoC placement and arrangements are arbitrarily and do not reflect the practical scenario.

information about its speed, location and direction of its movement, etc. One such innovative method has been proposed in [317]. The method uses off-chip antenna arrays. These arrays can be replaced with the AoC based arrays which will not only miniaturize the system, but also enhance its precision and reduce the complexity because of a straightforward integration of the AoC based arrays with the system.

- **5G MM-Wave based immature drone detection system:** : In [304], a novel method for the detection of an immature drone based on a 5G MM-Wave cellular system has been proposed. The system utilizes the off-chip antennas for the beam-forming function. The use of AoCs for the design of this valuable system is highly beneficial because of the MM-Wave band of operation. The resulting benefits include low cost, smaller size and easy integration of the AoC with the system.

K. SMART CITY: POTENTIALS, AND CHALLENGES

A tremendous development in information and communication technologies over last the two decades has given birth to the idea of the smart cities where the living population, government, economy, and environment will be sustainably interconnected to improve quality of life in the cities [318]. Few applications of a smart city include smart water networks, smart traffic networks, intelligent parking systems [319], [320], smart homes and buildings [321], [322], smart electricity management system, a smart waste management system [323], smart health and educational systems [322], smart libraries, and intelligent environment monitoring [324]. Wired and wireless communication can be adopted for the connectivity of different networks depending on the nature of the application within the scope of the smart city. Conventionally, RF technologies are utilized for wireless connectivity applications. Because of the bandwidth constraints at RF and demand of ever-increasing high speed, there is a dire need of innovative solutions and technologies for smart city applications [318]. One of the potential solutions is embracing the MM-Wave band for wireless connectivity. In addition, low power consumption and miniaturization are the utmost requirements for the smart city based wireless communication systems [306], [325], [327]. With the AoCs, the use of antenna arrays [328] for this application is an attractive choice. The use of the AoC for wireless technologies based smart city applications is shown in Figure 20 where multiple networks are interconnected wirelessly with the help of the AoCs in order to facilitate smooth and efficient operations and thus utilizing the resources in an intelligent and smart way.

It is important to note that smart city applications are mostly driven by IoT [326] and WSNs [319], [328]. A comprehensive discussion of these in the context of the AoC has already been done in Section III (B and G) of this paper. In addition, 5G is likely to be the future technology for smart city applications [324], as discussed in Section III (A) of the paper.

L. OTHER APPLICATIONS

Recent days have witnessed significant progress in the field of underwater communication for variety of applications. The underwater robots are used for various applications such as the exploration, mining, military uses, etc [329], [330]. The underwater sensors are utilized for different functions such as environmental monitoring, off-shore oil and gas fields monitoring [331], and ocean-related data collection [332]. Autonomous underwater vehicles make use of an acoustic system to perform the localization function since it offers low loss and isotropic radiation characteristics. However, the multipath occurrence is one of the limiting factors for underwater based acoustic systems. One potential way to solve this issue is the use of EM waves based localization method as the EM waves offer a uniform attenuation characteristic in underwater propagation [329]. This calls for an efficient, compact, low loss, and low cost antenna and thus AoC becomes an attractive choice for the underwater communication. However, the disadvantage associated with the EM waves based underwater communication is the increase in attenuation with a rise in the operating frequency [331]. To minimize the attenuation, the use of low frequencies is beneficial; however, this enlarges the profile of the AoC. Consequently, novel antenna miniaturization methods will be required to offset this issue. Keeping in mind the fact that no AoC has been designed yet for this application as per the authors' best knowledge, extensive research efforts are needed in this domain.

Furthermore, wireless communication for smart grid application to ensure power efficiency, cost-effectiveness, and compactness can be achieved by multiband AoCs. Wireless smart grid is a very promising technology and is in evaluation phase; however, not a single AoC has been designed yet

TABLE 5. The potentials, challenges, and future directions of the AoCs for the emerging and future applications: A Summary.

Application	Potentials and Advantages	Challenges and Future Directions
5G Transceivers	1) Offers compact, low cost and low loss Massive MIMO based MM-Wave phased arrays transceiver 2) Relaxes the linearity-efficiency trade-off for the receiver 3) Improves the power efficiency of RF front-end leading to less thermal management requirements and enhanced battery life 4) Promises an easy integration with the RF front-end	1) To mitigate mutual coupling issue among AoCs in close proximity for massive-MIMO based system 2) To achieve multi-band operation 3) To avoid RF and EM interference 4) To ensure an accurate measurement, especially on the spot testing 5) To achieve high performance to mitigate higher loss at MM-Wave 6) To facilitate dual polarization operation
IoT Wireless Devices	1) Offers low power, low cost and compactness advantages 2) Shifting of IoT operations at MM-Wave – a future trend- suites the use of the AoC	1) To achieve antenna miniaturization for low frequency devices 2) To Mitigate of performance enhancement issues
Testing of ICs & Antennas	1) Facilitates contactless, low-cost and interference-free testing of ICs & Antennas	1) To Extend the frequency up-to MM-Wave and THz band for the novel measurement setups 2) To achieve improvement in performance of AoC for a better measurement accuracy
WSNs	1) Offers cost-effective, low-profile and ultra-low power solutions	1) To propose antenna's miniaturization methodologies for low frequency applications 2) To promise an efficient transfer of wireless energy to a distanced remote sensor with a better range
Wireless Energy Transfer	1) Presents energy-efficient, low cost and low-profile designs	1) To secure a long range operation 2) To achieve high efficiency 3) To enable energy transfer to multiple places simultaneously 4) To propose antenna's miniaturization methods for low frequency applications
Biomedical Implants	1) Offers ultra-low power, compact, cost-effective, and an optimized EM energy harvesting based solutions	1) To propose novel AoC's miniaturization techniques 2) To ensure AoC's robustness 3) To mitigate performance degradation within the body tissues 4) To attain dual-band operation 5) To overcome EMI issues with other transceiver components
Wearable Electronics	1) Presents solutions with low power, low cost, low-profile, light-weight , higher reliability and more robustness	1) To propose antenna's miniaturization methods for low frequency operation 2) To overcome performance degradation with bending and contact with the human body 3) To relax the trade-off between antenna's performance and configuration/placement to avoid EMI issue
Wireless Interconnects Applications	1) Mitigates the issues offered by the traditional wired interconnects such as higher delay, large power consumption, limited bandwidth, and low data rate	1) To present antenna miniaturization methods for low frequency applications 2) To achieve performance/gain enhancement for the AoC 3) To mitigate the coupling issue among multiple nearby AoCs
Automotive Industry (SDCs etc.)	1) Offers compact integration of multiple antennas within the vehicles	1) To achieve multi-band operation 2) To present antenna miniaturization methods for low frequency applications 3) To overcome the coupling issues among multiple closely-spaced AoCs
UAVs/Drones	1) Offers advantages such as low cost, compactness, low weight, fabrication and integration easiness	1) To ensure multi-band operation 2) To enable antenna compactness at low frequencies 3) To ensure high efficiency for wireless energy transfer to UAVs
Smart City	1) Provides compact solutions with possible array implementation 2) Offers all the benefits associated with the 5G and IoT based AoCs	1) To facilitate the shift from low frequencies to MM-Wave 2) To achieve multi-band operation

for this application as per authors' knowledge. Both these facts make this an exciting future research area. In addition, the explosive development in wireless communication techniques and technologies has enabled the business and industry products to be portable and wearable. The smart watch is an excellent example of such products which has become ubiquitous these days and provide seamless wireless connectivity such as Wi-Fi, internet, and Bluetooth facilities [334], etc. The AoC, because of its miniaturized nature, becomes a superior choice for this application. The AoC also enables the use of MIMO antenna arrays for the data rate enhancement without any significant increase in the size. The multi-band operation, miniaturization, and the insensitivity of antenna's performance with an interaction with the hand phantom are few key challenges of the realization of such AoC and therefore a promising future research domain. A lucid summary of the potential applications with respect to the AoCs is provided in Table 5.

IV. CONCLUSION

Keeping in view the enormous benefits offered by the AoCs and to evaluate their suitability for the evolving applications, this article presents a thorough survey on the potentials and challenges of the AoCs for the emerging application areas. The article commences with the current state-of-the-art of the AoC's application areas which reveals that the AoCs are suitable for a multitude of a diverse set of applications. In this section, a detailed study has been performed on the recent application domains of the AoCs. The recently designed AoCs have been presented in a well-structured and organized form and have been divided into three categories from their application's perspective: MM-Wave, THz, and low-frequency bands. This classification shows that the recently designed AoCs in the MM-Wave band outnumber the other two types followed by the AoCs designed in THz band with a conclusion that the AoCs are well-suited for all the bands, especially for MM-Wave and THz band applications.

In the second part of the paper, the potentials of the AoCs for the most emerging and future applications have been delineated along with the detail of the advantages and the challenges offered by these applications. In addition, a few methods to mitigate some of these challenges as well as future directions in this regard have been described in a concise way. Consequently, a list of the promising emerging applications well-suited for the AoCs has been compiled. These applications include 5G, IoT, WSNs, IC's and antenna measurement, flexible electronics, biomedical implants, wireless energy transfer, RF energy harvesting, Inter and Intra chip wireless communication, automotive industry including SDCs, drones, smart city, underwater communication, smart grid, and smart watches. Based on the results of this study, it can be safely predicted that the AoCs will get more prevalent in the future. It is anticipated that this well-disciplined and coherent survey will serve as an excellent self-awareness platform for the relevant researchers and will attract their attention towards the use of the AoCs for the emerging applications. In addition, this paper is conceived to serve as a catalyst for the research community to come up with novel solutions for the highlighted problems and challenges in order to pave a path for the success of the AoCs for the state-of-the-art applications.

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