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Retrospect and Prospect on Integrations of Millimeter-Wave Antennas and Non-Millimeter-Wave Antennas to Mobile Phones

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ABSTRACT Informative retrospect and inspiring prospect on various creative and interesting integrations of millimeter-wave (mm-Wave) and non-mm-Wave antennas to mobile phones from diverse and practical perspectives are innovatively and systematically presented in this article. Therefore, quick and beneficial understanding of reported works can be achieved and further influential developments can be enlightened. The types of the proposed integrations include the printed circuit board (PCB) type, module type, the flexible printed circuit (FPC) type, the exterior type, the hybrid type, and the display type, which are in the discussion order of straightforwardness for solution generation. View angles from the locations, conformality, and transparency of the integration solutions are presented as well to comprehensively compare the six kinds of discussed antenna integrations to mobile phones. Also, an insightful evolution of the analyzed antenna integrations to mobile phones is illustrated as the summary to enable a clearer picture of the solution considerations, features, and trends.

INDEX TERMS 5G mobile communication, antennas, cellular phones, integration, millimeter-wave.

I. WHY ANTENNA INTEGRATIONS TO MOBILE PHONES?

Due to the higher requirements on wireless data rates in the era of the 5th generation mobile communications (5G) than those in 4G, the mm-Wave bands possessing wide bandwidths able to upgrade channel capacities and thus user experience in wireless communications are the core spectrum to 5G or even 6G technologies [1]–[3]. According to the 3rd generation partnership project (3GPP) [4], currently, the licensed mm-Wave bands for 5G are coded as bands n258 (24.25–27.50 GHz), n257 (26.5–29.5 GHz), n261 (27.50–28.35 GHz), n260 (37.0–40.0 GHz), n259 (39.5–43.5 GHz), and n262 (47.2–48.2 GHz). However, in addition to mm-Wave bands, non-mm-Wave bands for 5G and long-term evolution (LTE) bands are still essential to attain satisfied wireless coverage with acceptable wireless transmission rates defined by the radiocommunication sector of the international telecommunications union (ITU-R) [5]. Among the coded 5G licensed non-mm-Wave bands by the 3GPP [6], not only the re-farmed bands, but also the bands n77 (3.3–4.2 GHz), n78 (3.3–3.8 GHz), and n79 (4.4–5.0 GHz) are prevailing in most countries and areas nowadays. In other words, for 5G, the mm-Wave and non-mm-Wave bands in fact are complementary to each other for the hotspot and wide coverage scenarios described by ITU-R, respectively, to ensure and enhance user experience in 5G wireless communications. As a result, mm-Wave antennas for 5G and non-mm-Wave antennas for 5G and/or for LTE are reasonably anticipated to co-exist in most 5G mobile phones. Besides, to support the user experienced data rate [5] proposed by ITU-R in non-mm-Wave bands, the technology of massive multiple-input and multiple-output (MIMO) is hence adopted, which implies more non-mm-Wave antennas should be deployed in a mobile phone to establish more channels for better wireless transmissions. Owing to so limited internal space of mobile phones and more antenna quantities in mobile phones,

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especially the 5G ones, the integrations of mm-Wave and non-mm-Wave antennas are highly foreseeable and favorable to future mobile phones because the space occupied by various antennas is promising to get reduced through integrations. To put it differently, in addition to the realization of the original individual wireless communication functions, the integrations of mm-Wave and non-mm-Wave antennas can further achieve the compelling and precious synergy, that is, the prevention from undesirable size expansion caused by antennas or even the reduction in whole sizes of mobile phones. Moreover, the integrated mm-Wave and non-mm-Wave antennas can serve as one-stop antenna total solutions to mobile phones, which can remarkably benefit the design loads, assembly complexity (i.e., the yield rates and assembly efficiencies), and even the overall costs. Therefore, the topic on integrations of mm-Wave and non-mm-Wave antennas to mobile phones has attracted much attention and wide interests. In this article, five creative and interesting types, including the PCB type, module type, FPC type, exterior type, and hybrid type, for the integrations of mm-Wave and non-mm-Wave antennas to mobile phones are retrospectively presented; what's more, the promising and innovative integration, the display type, is prospectively proposed. Based on the retrospect and prospect, an enlightening evolution of integrations of mm-Wave and non-mm-Wave antennas to mobile phones from diverse and pragmatic angles of views is inspiringly analyzed and depicted as well for more straightforward and insightful understanding to pave for future developments.

II. TYPES OF INTEGRATIONS

A. PCB TYPE

For past and current mobile phones, PCBs are fundamental and necessary system platforms to carry components and traces. Furthermore, PCBs are also popularly employed for designs of mm-Wave antennas [7], [8] and non-mm-Wave antennas [9], [10]. Consequently, it makes certain sense to design the PCB-type integrations of mm-Wave and non-mm-Wave antennas [11]–[14] as shown in Fig. 1. The integrated design in Fig. 1(a) [12] covers two mm-Wave bands (28 GHz and 38 GHz) and five non-mm-Wave bands (2.3 GHz, 2.4 GHz, 2.5 GHz, 3.5 GHz, and 5.0 GHz) through two substrate integrated waveguides (SIWs) (individually with a 1×4 mm-Wave slot antenna array) reused as parts of two non-mm-Wave antennas coupled by a planar T-shaped probe. In Fig. 1(b) [13], two slots on the PCB are opened to serve as the integrated antennas for mm-Wave bands (23–29 GHz) and non-mm-Wave bands (2.05–2.70 GHz). Nevertheless, PCB-type antennas typically require significant clearance areas or slots on PCBs; thus, the application feasibility to practical mobile phones, especially the 5G ones with competitive phone sizes, plenty of components, and high screen-to-body ratios, generally will be impacted obviously.

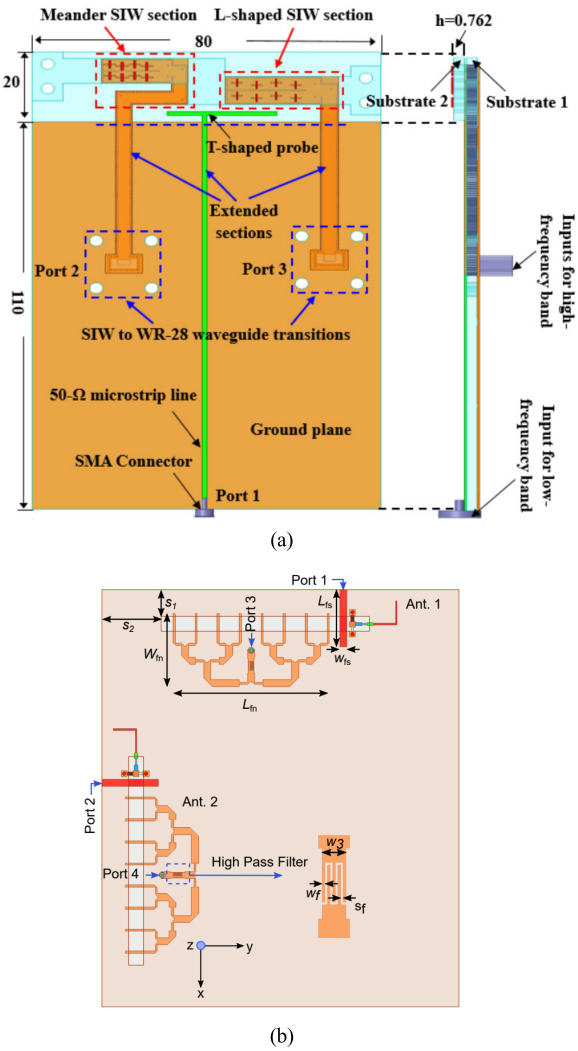


FIGURE 1. (a) Two SIWs (with mm-Wave slot antenna arrays) as parts of two non-mm-Wave antennas on a PCB [12]. (b) Two slots on a PCB as the integrated mm-Wave and non-mm-Wave antennas [13].

B. MODULE TYPE

Because the antenna-in-package (AiP) solution is to integrate the antenna(s) and radio-frequency integrated circuit(s) (RFIC(s)) into a standard surface-mounted package [15], [16] to shorten the in-between feeding paths and hence to mitigate the corresponding path losses for better radiation performance, the AiP solution [17]–[19] nowadays is the mainstream to mm-wave antennas in terminal devices, fixed wireless access (FWA) stations, and base stations. Due to the packaging processes, the AiP solution typically is in the module type; to accomplish the discussed integrations, non-mm-wave antennas are rationally integrated to existing mm-wave AiP modules. In other words, the module type is a good candidate for integration solutions of mm-Wave and non-mm-Wave antennas, especially to mobile phones. To date, almost studied and commercialized 5G AiP modules for handsets are only to cover 5G mm-Wave bands. In order to expand the band coverage on 5G non-mm-Wave bands, a leading and innovative mm-Wave AiP-based module named mm-Wave antennas-in-package integrating non-mm-Wave antennas (AiPiA) [20], [21] shown in Fig. 2(a)

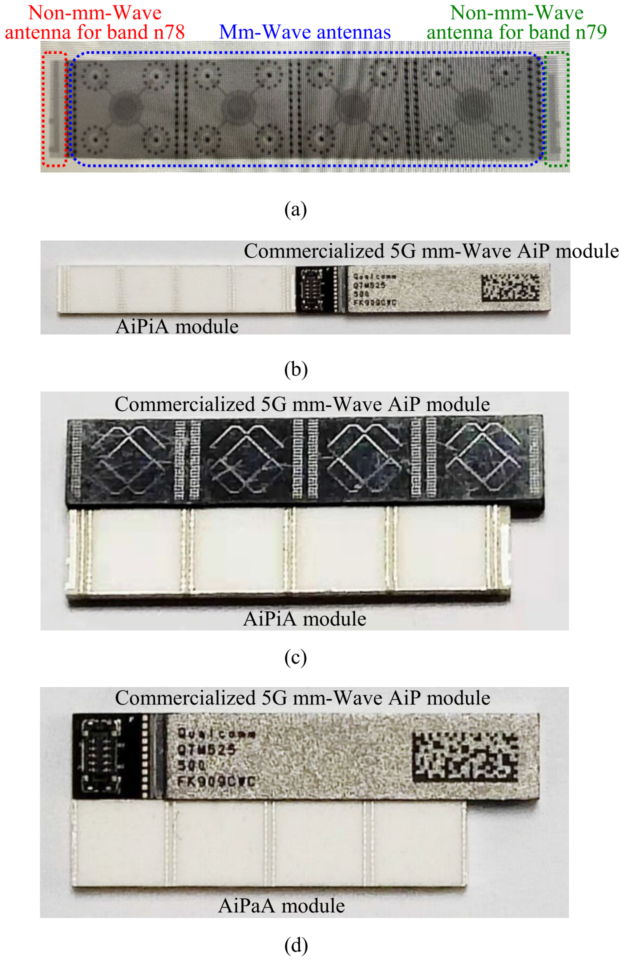


FIGURE 2. (a) The X-ray image of the AiPiA module prototype (21.27 × 4.18 × 1.36 mm^3) [20]. (b) and (c) The size comparison between the AiPiA module prototype [20] and a commercialized mainstream 5G mm-Wave AiP module [17]. (d) The size comparison between an LTCC-based AiPaA module prototype (19.39 × 4.18 × 1.36 mm^3) [20] and a commercialized mainstream 5G mm-Wave AiP module [17].

was presented. The AiPiA module is to integrate two physical non-mm-Wave antennas for 3GPP 5G bands n78 and n79 to a 5G multi-band mm-Wave AiP module (with the low-temperature co-fired ceramic (LTCC) as the substrate) covering 3GPP 5G band n257, n261, n260, and the mm-Wave band (24.75–27.50 GHz) planned in China to realize a total solution of 5G antennas to mobile phones. The uniformly-spaced mm-Wave antennas of the 1 × 4 mm-Wave antenna array in the AiPiA module are in the form of cavity-backed differential inverted-L antennas with two floating circular patches; two such differential pairs of inverted-L antennas are orthogonally placed in the cavity for dual-polarized radiations to mitigate the wireless link-drop rates and to attain MIMO operations for higher transmission rates. The two integrated physical non-mm-Wave antennas are in the type of modified inverted-F antennas (IFAs); the two modified IFAs are extending along the AiPiA module height with their ends upward to the free space, not to the PCB bottom ground. Therefore, clearance areas on the PCB bottom ground are not required so that the application practicability of the AiPiA module is greatly enhanced. The in-band isolation between the mm-Wave and physically integrated non-mm-Wave antennas is higher than 25.82 dB. Fig. 2(b) and Fig. 2(c) show size comparisons between the AiPiA module prototype [20] and a commercialized mainstream 5G mm-Wave AiP module [17] also of a 1 × 4 mm-Wave antenna array for mobile phones. From Fig. 2(b) and Fig. 2(c), it can be observed that the AiPiA module prototype is shorter than the commercialized mainstream 5G mm-Wave AiP module with their widths equal. Additionally, an AiPiA design derivative to achieve MIMO functions both in mm-Wave and non-mm-Wave bands was reported [20], too. Furthermore, to reduce the AiPiA module volume, another innovative module of the mm-Wave AiP-based design called mm-Wave antennas-in-package as non-mm-Wave antennas (AiPaA) was proposed [20], [22] to directly feed the 5G mm-Wave AiP module (also covering 3GPP 5G band n257, n261, n260, and the mm-Wave band (24.75–27.50 GHz) planned in China) by the 5G non-mm-Wave sources and feeding networks so that the 5G mm-Wave AiP modules themselves can function as virtual equivalent (i.e., no physical non-mm-Wave antennas integrated) 5G non-mm-Wave antennas for 3GPP 5G bands n78 and n79 as well to enable an even more advantageous 5G antenna total solution than the AiPiA one. The in-band isolation between the mm-Wave and virtual equivalent non-mm-Wave antennas is higher than 21.15 dB. Besides, the size comparison between a commercialized 5G mm-wave AiP module [17] and an AiPaA module prototype [20] also based on the LTCC substrate is shown in Fig. 2(d); noticeably, the length of the presented AiPaA module is much shorter than that of the commercialized 5G mm-Wave AiP module with the same widths. Moreover, an AiPaA design derivative for both mm-Wave and non-mm-Wave MIMO functions was proposed [20], too. In addition, an advanced hybrid design concept through the combination of AiPiA and AiPaA designs named mm-Wave antennas-in-package integrating and as non-mm-Wave antennas (AiPiaA) was presented [20] to attain a mm-Wave AiP module with even more non-mm-Wave antennas (that is, the stronger capabilities of non-mm-Wave wireless communications) in both physical and virtual equivalent forms in a competitive module volume. One of the keys to the AiPiaA design is the isolation between these included non-mm-Wave antennas; what's more, when some of the mentioned non-mm-Wave antennas operate in the same bands, their envelope correlation coefficients (ECCs) are core to the wireless communication performance as well.

C. FPC TYPE

FPC antennas for non-mm-Wave bands have been popularly applied to mobile phones [23]–[25] for a long time. Also, the conformal ability of the FPCs is much better than that of the modules, which means the FPCs can better fit the curved and sleek shapes of mobile phones to further reinforce attractiveness and competitiveness of mobile phones. Consequently, to integrate mm-Wave and non-mm-Wave antennas

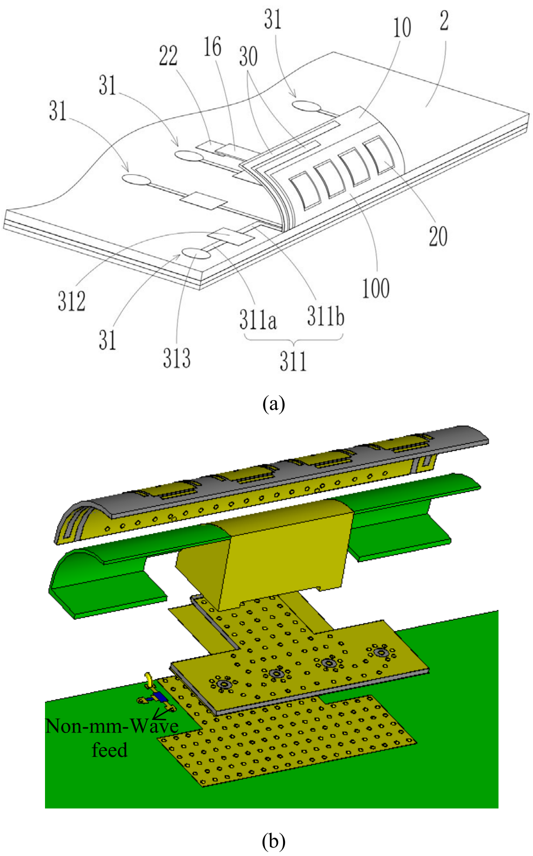


FIGURE 3. (a) Mm-Wave and non-mm-Wave antennas integrated on an FPC [26]; (b) the exploded view of an FPC-based integration of mm-Wave and non-mm-Wave antennas [27].

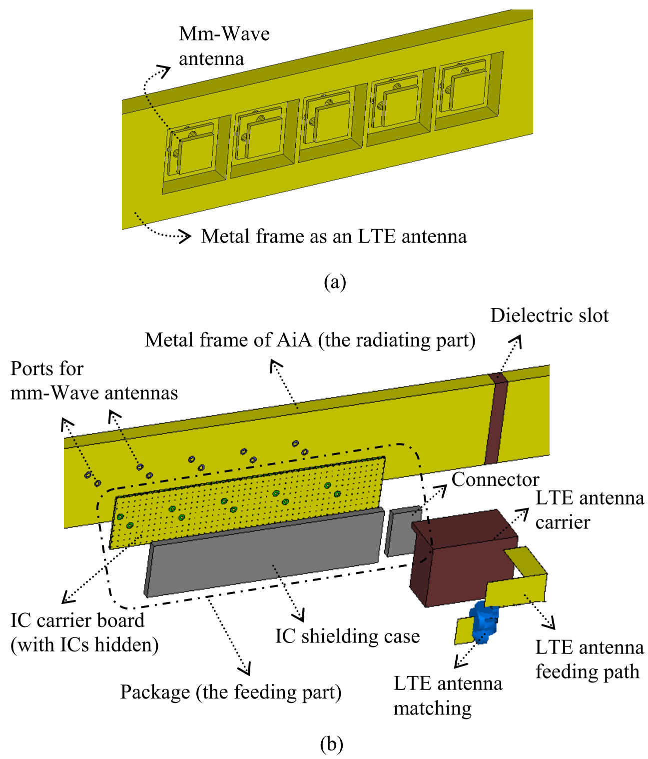


FIGURE 4. (a) Mm-Wave antennas embedded in a metal frame of a mobile phone as an LTE antenna, i.e., the AiA design [28]; (b) exploded view of AiAiP solution [28].

based on FPCs is reasonable and promising. As shown in Fig. 3 (a) [26], a flexible integration of mm-Wave and non-mm-Wave antennas based on an FPC was proposed. In the figure, the part 2 means the PCB, part 10 stands for the FPC, part 100 is the flexible antenna structure, part 16 represents the extended portion (for mm-wave signal transmissions) from the FPC, parts 31 symbolize the feeding source assembly for non-mm-Wave antennas (with the part 311 as the feeding line, part 312 as the matching network, and part 313 as the feeding source), part 22 refers to the mm-Wave RFIC, parts 30 mean the physical non-mm-Wave antennas, and part 20 stands for the mm-Wave antennas. As a result, in this design, totally four non-mm-Wave antennas, two physical ones (parts 30) and two virtual equivalent ones functioned by the FPC itself directly fed by the non-mm-Wave antenna feeding source assembly (parts 31), are integrated on the same FPC (part 10) originally for the mm-Wave antennas. Likewise, the isolation (and ECCs for antennas operating in the same bands) between the four integrated non-mm-Wave antennas is crucial to the design success. What deserves attention is the substrates of low loss tangents (e.g., the liquid crystal polymer, LCP) should be employed for the FPCs carrying the mm-Wave antennas to achieve better mm-Wave radiation performance. In Fig. 3(b) [27], the exploded view of an FPC-based conformal integration of a 1 × 4 uniform mm-Wave antenna array (for band n261) and two virtual equivalent non-mm-Wave antennas (for band n79) fed by two non-mm-Wave sources is shown as well. The gray part is the flexible low-loss dielectric substrate, the yellow ones are metal, the green ones are the FR4 board and antenna carrier, and the blue ones represents the matching components.

D. EXTERIOR TYPE

Currently, for most mobile phones, inclusive of 5G ones, the metal exteriors, especially the metal frames, are the popular styles because the metal exteriors are not only the appealing features to customers but also the durable protection structures for mobile phones from being damaged easily. Thus, for the handsets with (5G) mm-Wave wireless functions, the mm-Wave antennas in general have to co-exist with metal exteriors [28]–[30]. Besides, it is very popular and mature for mobile phones to employ metal exteriors as non-mm-Wave antennas for LTE or 5G [31]–[33]; therefore, the metal exteriors are quite natural to be the carriers for the integrations of mm-Wave and non-mm-Wave antennas to mobile phones. To overcome the shielding effect of the metal exteriors (on the PCB-type, module-type, and FPC-type antennas), to mitigate the antenna radome effect of dielectric superstrates over mm-Wave antennas (as the filling or decoration parts for the on-metal antenna windows), and to reduce the internal occupied volumes by mm-Wave antennas, the mm-Wave antennas hence can be conformally relocated to the metal exteriors which function as non-mm-Wave antennas to accomplish the conformal integrated antenna designs. The integrated design called mm-Wave antennas in non-mm-Wave antennas (AiA) [28] based on the solution of antennas in metal exteriors (AiME) [28] was proposed in Fig. 4(a) accordingly. The uniformly-spaced mm-Wave antennas in Fig. 4(a) are in the type of stacked patches. The lower big patch is mainly for the low-band operation and the upper small one is primarily for the high-band performance. Furthermore, two feeding points of each mm-Wave antenna element are set on two centerlines of orthogonal edges of the upper small patch of the stacked patches to excite two polarizations, i.e., the vertical and horizontal ones (or the right-hand and left-hand circular ones). In terms of the simulated 10-dB impedance bandwidths, the integrated mm-Wave antennas can cover 27.44-28.56 GHz and 36.92-40.22 GHz for the vertical polarization, and 27.32-28.56 GHz and 36.96-40.34 GHz for the horizontal polarization to both support the 3GPP 5G mm-Wave bands n261 and n260. To put it differently, the mm-Wave antennas are dual-band dual-polarized. Additionally, in terms of the simulated 6-dB impedance bandwidths, the non-mm-Wave antenna in the form of a metal frame covers 872-962 MHz and 2265-2740 MHz to accommodate LTE Band 8 (880-960 MHz), Band 40 (2300-2400 MHz), and Band 41 (2496-2690 MHz). The in-band isolation between mm-Wave and non-mm-Wave antennas is higher than 46.81 dB. Moreover, to alleviate the feeding losses of the AiA design caused by the long feeding paths between mm-Wave antennas and mm-Wave RFIC(s), the upgraded solution named mm-Wave antennas in non-mm-Wave antennas integrating a package (AiAiP) [28] was innovatively presented in Fig. 4(b) to directly mount the mm-Wave AiP's feeding package (including the IC(s), IC carrier board, IC shielding case, and connector), i.e., without mm-Wave antennas, to the internal side of the meal frame as a non-mm-Wave antenna in the AiA design. Besides, a further derivative of a dual-polarized AiAiP to cover more 3GPP 5G mm-Wave bands, such as bands n258, n257, n261, and n260 was studied [28] as well.

E. HYBRID TYPE

As described above, owing to the popular both existence of mm-Wave AiP modules and metal exteriors in mobile phones with mm-Wave wireless functions, the combinations of mm-Wave AiP modules and metal exteriors consequently make great sense as the hybrid-type integration solution for mm-Wave and non-mm-Wave antennas to mobile phones. Due to the shielding effect on electromagnetic radiations, the metal exteriors in nature are negative to mm-Wave antennas deployed inside the handsets. That's the reason why mm-Wave antennas are relocated and embedded to metal exteriors as the AiME solution to avoid the shielding effect, or that's why mm-Wave antennas should be elaborately placed with main radiation directions not blocked by metal exteriors. In the two mentioned ways, the mm-Wave antennas

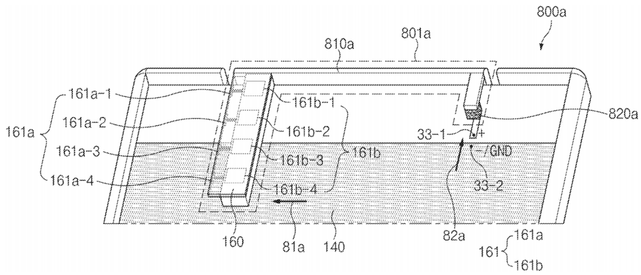
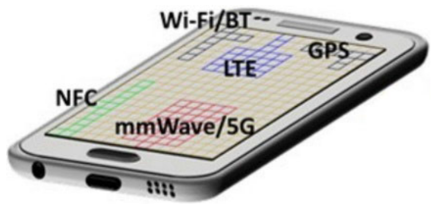


FIGURE 5. The hybrid integration of a mm-Wave AiP module and a non-mm-Wave antenna in the form of a metal exterior [34].

or mm-Wave AiP modules generally are not beneficial to metal exteriors no matter whether the metal exteriors serve as non-mm-Wave antennas or not; instead, the metal exteriors may benefit mm-Wave antennas as the antenna carriers, for examples, the ones in AiA designs, to accommodate the mm-Wave antennas. An interesting and innovative solution shown in Fig. 5 [34], on the contrary, was proposed to employ a mm-Wave AiP module for supporting a non-mm-Wave antenna implemented by a metal frame through the in-between electrical connections to attain a hybrid-type integration solution of mm-Wave and non-mm-Wave antennas. In Fig. 5, based on the referenced patent [34], the part 801a is the electrical path that operates as a legacy (i.e., non-mm-Wave) antenna, part 810a (part of 801a) is named the conductive side member which in fact can be understood as a metal frame, part 33-1 is the feeding point of the non-mm-Wave antenna, and part 160 is the 5G mm-Wave antenna module including the mm-Wave antenna arrays 161 wherein the part 161a is the patch antenna array and part 161b is the dipole antenna array. The metal frame 810a is electrically connected with the conductive region of the 5G mm-Wave antenna module 160. Through the hybrid-type integration solution combined from the mm-Wave antenna module and non-mm-Wave metal-exterior antenna, the device size is promising to get smaller with non-mm-Wave antenna performance (especially for the low bands, e.g., the sub-1-GHz ones) secured or even strengthened because the length of the non-mm-Wave antenna can be innovatively elongated. In other words, now, the mm-Wave antenna module is part of and beneficial to the non-mm-wave antenna functioned by the metal exterior. In addition to this design, it's also quite hopeful for further advanced and even more powerful hybrid solutions realized by the combinations of AiP, AiPiA, AiPaA, or AiPiaA modules plus the discussed AiA designs or the AiAiP solution (i.e., the metal-exterior-based ones).

F. DISPLAY TYPE

Owing to the higher and higher screen-to-body ratios (which thus significantly suppress the placement freedom and clearance areas for antennas) of mobile phones to upgrade visual experience of users, the innovative antenna-on-display (AoD) solution [35]–[38] was presented to enable antennas compatible with displays. For the AoD solution, antennas are



(a)

(b)

FIGURE 6. **(a) Conceptual placements for AoD-based mm-Wave and non-mm-Wave antennas [37]; (b) the prototype of a 5G smartphone with the mm-Wave AoD solution [38].**

designed on displays (but under front cover glasses), for instance, in the form of imperceptible metal meshes so that the designed antennas are invisible to users. Furthermore, through the AoD solution, lower possibility of blockage (by hands or metal) on the antennas in the main use scenarios, wider spatial coverage of beams, and good conformality to the displays can be achieved, too. As shown in Fig. 6(a) [37], various separate antennas, including mm-Wave and non-mm-Wave ones, based on the AoD solution to a mobile phone are conceptually illustrated. However, the shown mm-Wave and non-mm-Wave antennas are not integrated. Also, although the details or concepts of the integration designs of AoD-based mm-Wave and non-mm-Wave antennas haven't been published yet (to the best knowledge of the authors), it is quite reasonably promising to accomplish the display-type integration of mm-Wave and non-mm-Wave antennas by utilizing the common platforms, e.g., the imperceptible metal meshes laminated on the displays. Through the integrations of mm-Wave and non-mm-Wave antennas based on the AoD solution, total sizes of the integrated antennas can get smaller than the size sums of the separate AoD-based antennas, which can mitigate the negative impacts on the visual and touch experience (especially when the antennas are designed on the same metal meshes for touch panels) thanks to fewer grids needed to be broken on the metal meshes to form antennas. The above five discussed types (namely, the PCB type, module type, FPC type, exterior type, and hybrid type) for integration solutions of mm-wave and non-mm-wave antennas to mobile phones generally are non-transparent to light and hence to sight. In comparison with the visually non-transparent (i.e., visible) types, the AoD solution is the visually transparent (i.e., invisible) type; as a result, the AoD solution is nicely beneficial for antennas (the intangible features to users) to co-exist with displays (the tangible features to users). Similarly, through the AoD solution, the functions and values of displays are enhanced as well due to the equipped wireless communication capabilities.

III. EVOLUTION

As shown in Fig. 7, rather than follows the time sequence of the publication, the evolution of the above analyzed integration solutions of mm-Wave and non-mm-Wave antennas to mobile phones actually is inspiringly depicted mainly based on the straightforwardness of the solution generation, that is, based on the easiness and rationality to trigger the thought extension, in the order from the reported to promising ones. The vertical axis shows primary advantages or the salient philosophy of the solutions; four horizontal axes are illustrated to represent the carriers, locations, conformality, and (visual) transparency of the mentioned solutions, respectively. As described in the subsection A of the Sec. II, because the PCBs are the fundamental and necessary platforms to past and current mobile phones, the antenna integration evolution therefore naturally debuts from the PCB type with the PCBs reused as the solution carrier.

Nonetheless, the PCB-type antennas (and their integrations) generally are not so practical to competitive mobile phones owing to the typical needs of large clearance areas and of modifications (e.g., slots) on the system PCBs which carry lots of components and traces. The integration evolution thus transitions to the current mainstream type of mm-Wave antennas for terminal devices, that is, the module type with the mm-Wave AiP modules as the solution carrier. To put it differently, it is quite reasonable to reuse the current mainstream solution, i.e., the conventional or commercialized mm-Wave AiP modules, for expanding coverage on non-mm-Wave bands by integrating physical or/and by functioning as virtual equivalent non-mm-Wave antennas.

Additionally, due to good maturity, wide applications, and elegant conformality, the FPCs are very straightforward to be considered as the appealing carriers for the mm-Wave and non-mm-Wave antenna integrations accordingly.

Besides, because of the popularity of the metal exteriors for mobile phones, the prevailing applications of the metal exteriors as non-mm-Wave antennas for mobile phones, and the avoidance of metal shielding (on the PCB-type, module-type, and FPC-type), to integrate mm-Wave and non-mm-Wave antennas with the metal exteriors as the carrier to be the exterior-type solution for realizing metal compatibility consequently is the next progress.

Moreover, in view of the prevalent both existence of the two parts (i.e., two resources), the mm-Wave AiP modules and metal exteriors in mobile phones with mm-Wave wireless functions, the interesting and inspiring integration to combine the two existing resources as the hybrid-type solution with both the mm-Wave AiP modules and metal exteriors as the solution carriers is hence proposed so that the mm-Wave AiP modules can innovatively benefit the non-mm-Wave

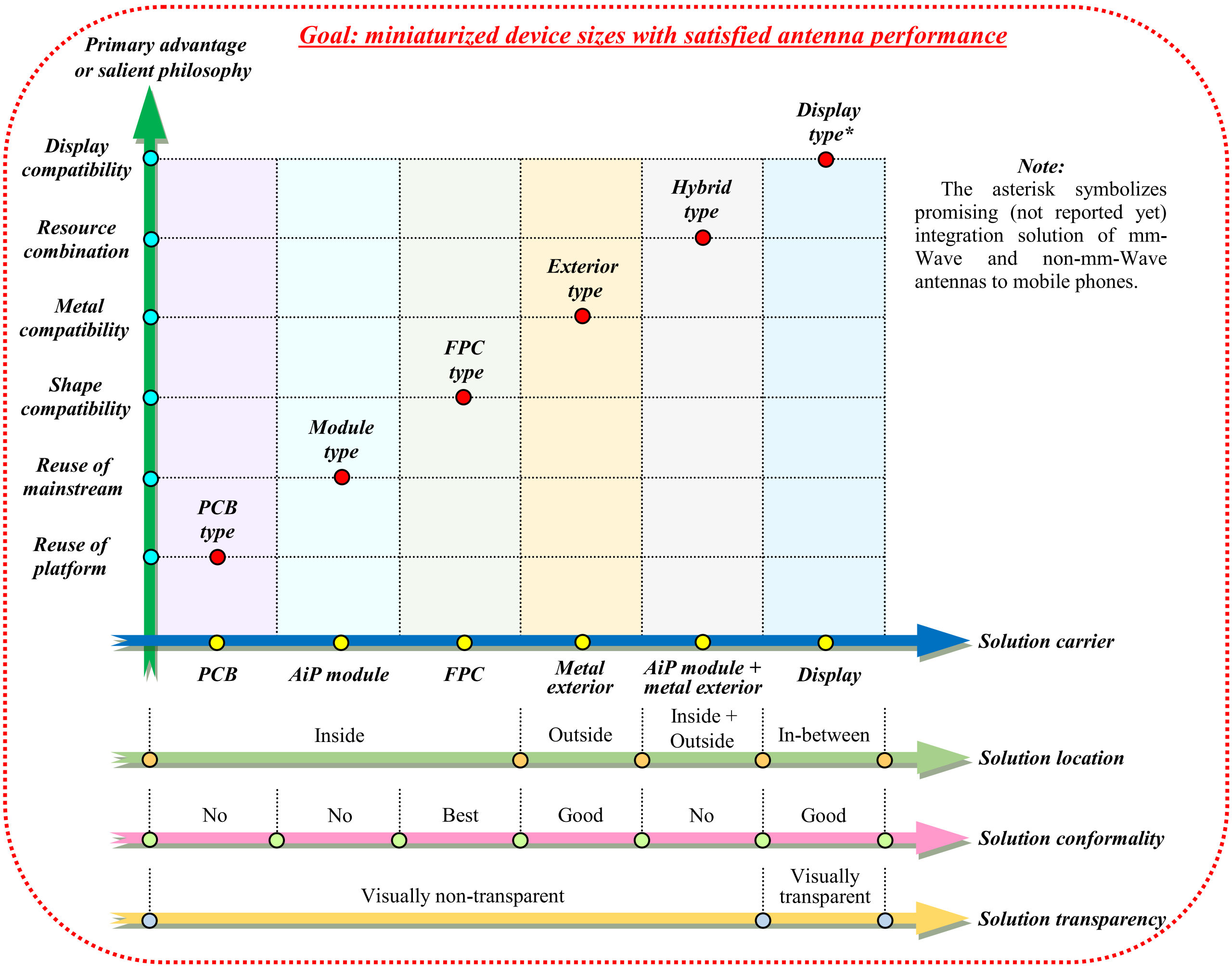


FIGURE 7. **Promising evolution for integration solutions of mm-Wave and non-mm-Wave antennas to mobile phones.**

antennas in the form of metal exteriors. What's more, likewise, based on the philosophy of resource combination, it is also foreseeable and practical that FPC-type solution can be combined with the module-type solution, such as the AiP, AiPiA, AiPaA, or AiPiaA, or/and the exterior-type solution as well to trigger even more novel, more competitive, and more advanced new hybrid integration solutions of mm-wave and non-mm-wave antennas to mobile phones. The described integration solutions of the PCB type, module type, FPC type, exterior type, and hybrid type in principle are not placed to face users. By contrast, the innovative and promising display-type integration based on the AoD solution deploying invisible antennas on the displays (i.e., the solution carrier) to enable the compatibility of displays, the salient and kernel features of current mobile phones, where the antennas can be located to face users for more creative applications (in addition to the mentioned cellular communications), e.g., the mm-Wave radio detection and ranging (Radar) for gestures, faces, or motion recognition, emerges after the mentioned hybrid-type solution.

As for the solution locations, the PCB-type, module-type, and FPC-type solutions normally are inside mobile phones; the exterior-type solution is on the outsides of mobile phones. The hybrid-type solution is both inside and on outsides of mobile phones, and the display-type one is laminated between the front cover glass and the display (an exposed part). In other words, the trend of the solution locations moves from inside to the exposed parts of the mobile phones.

Furthermore, for the solution conformality, a very critical characteristic to mobile phones, the PCB-type integration solution is planar and conformal to boards, typically not to the discussed curved and sleek shapes of mobile phones (for attractiveness and competitiveness reinforcement). For the module and hybrid types, currently, they are not conformal; in general, the FPC type is the best at conformality with the exterior and display types good at this.

In terms of visual transparency of solutions, the PCB-type, module-type, FPC-type, exterior-type, and hybrid-type ones basically are visually non-transparent; that is, visible and light blocking. The display-type solution, however, is invisible, i.e., visually transparent, to users so that the optical properties of the displays can be better secured. To put it differently, the trend of the solution transparency progresses from visual non-transparency to visual transparency.

Moreover, to prevent the blockage by hands, heads, and metal, multiple antennas, especially the mm-Wave antennas (and their integrations with non-mm-Wave antennas), typically are deployed at diverse locations (for a mobile phone) with the switching algorithms applied for antenna triggering to ensure wireless performance [39]–[41].

Last but not least, the red dashed frame in Fig. 7 stands for the fundamental and prime framework and the core goal, namely, miniaturized device sizes with satisfied antenna performance, for all the presented and predicted integration solutions of mm-Wave and non-mm-Wave antennas to mobile phones.

IV. CONCLUSION

By integrating mm-Wave and non-mm-Wave antennas to mobile phones, in addition to securing the original functions, the precious synergy of reduction in total occupied volumes by the originally separate antennas can be also elegantly attained so that the product competitiveness can be well strengthened. The systematic and informative retrospect on the five kinds of reported integration solutions (the PCB type, module type, FPC type, exterior type, and hybrid type) and the enlightening and interesting prospect on the two kinds of promising integration solutions (the display type, and advanced new hybrid one) are both insightfully proposed from diverse and pragmatic perspectives. Future developments and researches on the attractive and critical topic can thus be greatly excited, benefited, and facilitated.

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