2.
LITERATURE REVIEW

2.1 Introduction

The popularity of mobile communication systems have increased extremely during the last decade and the market needs still continue to increase that contributes to the growth and development of variety of antenna structures for getting multiband and wideband functionality. Therefore, the placement of antenna is changed from external to internal. In the recent years, various promising antenna structures are available in the market for modern day mobile phones. All the antennas have their own characteristics. Based on the features like compact size, reasonable bandwidth, good radiation performances, and robust performances in the presence of user hand and head, antenna designer can select the appropriate antenna for mobile phone applications. In the following sections relevant literature survey is given.

2.2 Literature Review

In 1987, Katehi *et al.* discussed bandwidth enhancement methods for electromagnetically coupled microstrip dipoles antenna. Substantial bandwidth enhancements were obtained when the parasitic metallic strips were incorporated in the structure [Katehi *et al.* (1987)]. Later, Berg and Katehi (1991) presented bandwidth enhancement technique for microstrip fed slot arrays [Berg and Katehi (1991)].

In 1994, Pedersen and Andersen presented a remedy of the SAR problems associated with the whip antennas a full short circuit planar inverted-F antenna (FS-PIFA) which was mounted on the back side of the housing of the hand-held device [Pedersen and Andersen (1994)]. Further, Fuhl *et al*. [Fuhl *et al*. (1994)] analyzed performance of a radiation-coupled dual-L antenna (RCDLA). The antenna was mounted on the back side of the hand-held terminal, making use of the metallic housing as a shielding structure. The simulations show that this structure has a similar performance to that of the recently proposed full short circuit planar inverted-F antenna (FS-PIFA) in terms of shielding and radiation characteristics. Noguchi *et al*. described the radiation characteristics of a meander line antenna and way to improve impedance matching by using two strips [Noguchi *et al*. (1996)]. Later, Virga *et al.* addressed the development and characterization of several low-profile integrated antennas with enhanced bandwidth for wireless communications systems [Virga et al. (1997)]. Authors' demonstrated that the new radiators are developed by adding parasitic elements or tuning devices to the planar inverted-F antenna (PIFA). Rowley and Waterhouse investigated the application of two different types of novel shorted-patch antennas for mobile communications handsets at 1800 MHz. A single shorted-patch and a stacked shorted-patch antenna offering improved bandwidth and compared with data for a $\lambda/4$ monopole [Rowley and Waterhouse (1999)]. Salonen *et al*. described a novel dual-band planar inverted F- antenna (PIFA) for wireless local area network applications [Salonen *et al*. (2000)]. Afterward, Tong *et al*. described a stacked, dual-frequency microstrip planar inverted-F antenna (DF-PIFA) for mobile telephone handsets that can concurrently work in two frequency-bands [Tong *et al*. (2001)]. Wang *et al*. investigated a novel internal square patch antenna by introducing a single shorting pin and a thin rectangular slot perforated in a square patch for the application of the 3G IMT-2000 mobile handsets [Wang *et al*. (2001)]. Lui *et al*. [Lui *et al*. (2001)] (2001) introduced three basic methods for incorporating the LC resonator into the dual frequency PIFA, including a variant of the meandering PIFA. Karmakar *et al*. [Karmakar *et al*. (2001)], proposed a dual-band dual-feed planar inverted-F antenna (PIFA) and demonstrated that the corner truncation of the patch is less sensitive to the resonant frequency than the patch lengths, but the corner truncation has no adverse effect on the radiation characteristics of the PIFA.

Vazquez *et al*. [Vazquez *et al*. (2002)] proposed a compact antenna suitable for personal communication handsets. The antenna consisted of a rectangular patch with a shorting pin. A spur-line filter was added to obtain a dual-band operation. Further, Wu and Wong in 2002, presented the effects of ground-plane dimensions on the impedance bandwidth of a planar inverted-F antenna for

UMTS band mobile handset [Wu and Wong (2002)]. Hsiao *et al*. [Hsiao *et al*. (2002)], obtained 900 and 1800 MHz dual band operation by embedding a branch-line slit in the radiating patch of a planar inverted-F patch antenna. The embedded branch-line slit has two branch slits one long folded slit and the other short bent slit for dual frequency operations. In 2002, Chen *et al*., presented a planar dual-L antenna with a novel tuning technique for an integrated GPS/PCS dual-band application [Chen *et al*. (2002)]. Soon after, Chiu and Lin [Chiu and Lin (2002)], presented a newly designed dual-band planar inverted-F antenna with three radiating resonators for use in mobile phone devices. Yeh and Wong (2002), illustrated the frequency ratio of the antenna's first two resonant frequencies can be controlled by loading a chip inductor of suitable inductance (about 12 nH or less) to a planar inverted-F antenna (PIFA) with a shorted rectangular spiral strip [Yeh and Wong (2002)]. Further, Chang and Wong [Chang and Wong (2002)] proposed a monopole antenna which was easily constructed by folding a planar meandered patch into a rectangular-tube-like structure for achieving GSM/DGS band operations. Lee and Wong [Lee and Wong (2002)] presented a novel very-low-profile monopole antenna for applications in GSM/DCS dual-band mobile phones. Soon after, Lee *et al*., designed a ceramic chip antenna having a new shape by utilizing the backside of the ceramic substrate for bluetooth applications [Lee *et al*. (2002)].

In 2003, Wong *et al.* [Wong *et al.* (2003)] proposed a novel planar monopole antenna with a very low profile and capable of multiband operation which consists of a planar rectangular radiating patch with folded slit at the bottom edge of the patch. Thereafter, Karmakar *et al.* [Karmakar *et al.* (2003)] described a RF switches which were integrated to the shorting strips of a single feed dual-band planar PIFA to make a tunable PIFA. Further, Guo *et al*. (2003) designed a new metal strip as an additional resonator which was directly connected with a feed strip and positioned at a plane perpendicular to a ground plane and a main dual-resonator patch radiator [Guo *et al*. (2003)]. Later, Peng *et al.*, presented a dual-band internal handset antenna (IHA) with a novel 3D structure [Peng *et al.*(2003)]. Therafter, Hsiao *et al.* [Hsiao *et al.* (2003)]

examined a novel dual-frequency PIFA with a rolled radiating arm suitable for GSM900 and DCS applications. Guo *et al.* [Guo *et al.* (2003)] presented a novel compact internal quad-band handset antenna for GSM900, DCS1800, PCS1900, and ISM2450 bands which consists of folded patches with a common shorting strip. Soon after, Yang *et al*. described an U-shaped slot loaded dual-frequency, single-feed, PIFA for GSM 900 and DCS 1800 band [Yang *et al*. (2003)]. Later, Ang *et al*. [Ang *et al*. (2003)] designed a compact internal quad-band antenna with two-layer folded patches which sharing a common shorting strip. Further, Chiu *et al*. [Chiu *et al*. (2003)] proposed a folded planar monopole antenna which was directly mounted at the top edge of the system ground plane without the need of an isolation distance.

In 2004, Sim *et al*. discussed an internal triple-band antenna fed by a microstrip line with two branches of meander line which was operated over PCS, IMT-2000, and Bluetooth bands [Sim *et al*. (2004)]. Further, Lee and Wong [Lee and Wong (2004)] proposed a novel internal monopole antenna which comprised two orthogonal wideband monopole elements, suitable for AMPS/ GSM/ DCS/ PCS quad-band mobile phones. Soon after, Shin *et al*. [Shin *et al*. (2004)] presented a novel design technique of the triple-band small internal antenna which covers GSM/ DCS/ IMT-2000 bands which consists of the double shorting posts, feed post, and the dual-crossed C-slot patch radiators. Later, Ciais *et al*. illustrated the design of a compact PIFA suitable for cellular telephone applications [Ciais *et al*. (2004)]. The quarter-wavelength antenna combines the use of a slot, shorted parasitic patches and capacitive loads to achieve multiband operation. Thereafter, Hossa *et al*. [Hossa *et al*. (2004)] described a new idea of increasing operational bandwidth of a compact PIFA by introducing open-end slots in the ground plane under the radiating patch. Qi *et al*. [Qi *et al*. (2004)] proposed a novel compact triple-band PIFA which consists of three strips operated at about 900 MHz, 1800 MHz, and 2450 MHz while sharing a common shorting strip and feed. Further, Chang *et al*. presented a novel low-profile GSM/DCS planar monopole antenna which was designed by folded and meandered planar monopole into a compact rectangular-box-like structure [Chang *et al*. (2004)]. Soon after, Guterman *et al*.

[Guterman *et al*. (2004)] described a novel microstrip patch antenna with a Koch pre-fractal edge and a U-shaped slot for multi-standard use in GSM1800, UMTS, and HiperLAN2 applications.

Nallo and Faraon proposed a new internal antenna for multiband cellphones applications which comprised a U-shaped elongated flat conductor featuring a closed meandered slot, a ground and a feed leg [Nallo and Faraon (2005)]. Further, Harackiewicz *et al*. [Harackiewicz *et al*. (2005)] presented a planar internal antenna for GPS/PCS dual band mobile phones. The presented antenna has two resonant printed elements, one is printed monopole element radiates at a higher frequency and couples electromagnetically to the other element. The other is the printed dipole element that radiates at a lower frequency and was placed around the monopole element. Further, Cho *et al*. suggested a novel miniature wideband internal antenna with dual monopole radiating elements for operating at multiband handset applications [Cho *et al*. (2005)]. It consisted of two radiating monopole elements with parallel connection in the limited handset interior space. Lee and Park [Lee and Park (2005)] proposed a novel compact and dual-band cable-fed patch antenna which covers GSM, DCS, and PCS bands. Two inductive parasitic on the ground plane and a gap capacitance was used to achieve compact and wideband characteristics. Soon after, Cho *et al*. (2005) analyzed a compact internal antenna of the modified PIFA type with a parasitic patch [Cho *et al*. (2005)]. It also considered the influences of the handset case and battery. Karkkainen [Karkkainen (2005)] studied a meandered multiband PIFA with two coplanar parasitic patches. The antenna has a very wide impedance bandwidth of 743 MHz covering the frequencies from 1.765 to 2.508 GHz with the $S_{11} \leq -6$ dB. Further, Park and Choi illustrated a novel and broad quad-band PIFA for cellular/PCS/UMTS/DMB applications [Park and Choi (2005)].

Kwak *et al*. [Kwak *et al*. (2006)] presented a new internal triple-band PIFA which covers GSM (880–960 MHz), DCS (1710–1880 MHz), and Bluetooth (2400–2484 MHz) bands. The geometrical parameters and electrical performances of the antenna can be obtained by cutting embedded slots on the patch surfaces and realizing electric via holes between two layers of the patch. Further, Sim and

Choi [Sim and Choi (2006)] discussed a compact wideband modified PIFA with two shorting strips for 2.4/5.2-GHz WLAN operations. As a starting point, two-branch strip lines derived from the dipole antenna structure were used to achieve the desired resonant frequency. One of them is connected to two shorting strips with the different length and width, and those strips generated additional resonant modes. Wong *et al*. [Wong *et al*. (2006)] examined a novel thin GSM/DCS dual-band internal patch antenna with a 3 mm air-layer substrate. The antenna has two resonant modes at about 900 and 1800 MHz and easily excited by embedding a T-shaped slit in the antenna's top patch. Soon after, Borowiec and Slobodzian discussed a novel miniaturized printed monopole antenna suitable for cellular handset terminals [Borowiec and Slobodzian (2006)]. A substantial reduction in antenna size was achieved due to the use of the inverted-F antenna concept combined with a capacitive feeding system. The antenna operated over GSM 1800, PCS 1900, and UMTS, with VSWR $\leq$ 2.5. Hsiao and Lu [Hsiao and Lu (2006)] proposed a planar dual-meander-line antenna consisting of three branch strips for a low-profile GSM/DCS/PCS/WLAN multiband mobile handset. Further, Chan *et al*. demonstrated a method of coupling energy from balanced signal or network to unbalanced PIFA antenna which was used for wireless mobile applications [Chan *et al*. (2006)]. Park *et al*. [Park *et al*. (2006)] designed a electrically small and wideband PIFA that covered the GSM900/GPS/DCS1800/DCS1900/IMT2000/ WLAN/ DMB service bands. Soon after, Jung *et al*. illustrated antenna consisting of a feeding strip, shorting strip, and folded loop radiating element with embedded tuning notches, current flow on the surface of the loop radiator so that the resonant frequencies could be controlled independently by their size and position [Jung *et al*. (2006a)]. Jung *et al*. [Jung *et al*. (2006b)] proposed a novel multiband internal antenna which can be applied for GSM, GPS, DCS, PCS, and WCDMA band mobile handheld systems, by using a half-wavelength loaded line structure (HWLLS). The antenna combined structure of HWLLS and a shorted monopole. A gap was cut between the antenna shorting pad and the PCB ground plane of system. Then this gap was connected by a chip inductor in order to easily control the upper frequency bands, DCS, PCS, and WCDMA without degradation of resonant characteristics in the lower bands, GSM and GPS. Abdelaziz *et al*. presented a novel microstrip antenna with wide bandwidth, two different radiating elements connected together through a matched section and were embedded on a single layer structure [Abdelaziz *et al*. (2006)]. This structure offered a dual-band microstrip antenna by controlling the two resonance frequencies of the two elements. Further, Choi *et al*. [Choi *et al*. (2006)] described a design of an internal quad-band antenna (double-spiral structures) resonating at Cellular (824-894 MHz), DCS/PCS (1710-1880 MHz/1850-1990 MHz), and WiBro (Wireless Broadband Internet, 2300- 2390 MHz) system band by inserting the spiral slits corresponding to the resonant frequencies.

Kim *et al*. [Kim *et al*. (2007)] proposed new design concepts of the PIFA structure with a folded feeding structure which is implemented between the feed pin and radiators. These structures consisted of the U-shaped folded feeding technique and parasitic components with enhanced multiple impedance bandwidth which covered the GSM 850, GSM 900, DCS, PCS, WCDMA, and WIMAX2350 bands. Oh *et al*. introduced a Varactor-tunable slim antenna which combined the use of slot, planar inverted-L (PIL) patch and Varactor diode to obtain wide multiband operation and frequency tunability which covered DCS, PCS, UMTS, WiBro, ISM, and WLAN bands [Oh *et al*. (2007)]. Wong *et al*. [Wong *et al*. (2007)] presented a planar inverted-F metal-strip antenna suitable for Bluetooth headset application. The antenna has a low-profile appearance and can be embedded inside the housing as an internal antenna. Wu *et al*. proposed an electromagnetic compatible (EMC) internal patch antenna centered at the top portion of the thin smart phone or personal digital assistant (PDA) phone [Wu *et al*. (2007)]. The EMC antenna in this study is encircled by an L-shaped shielding wall, which also served as part of the antenna’s ground plane and is centered above the top edge of the system ground plane. Park *et al*. [Park *et al*. (2007)] presented a novel design method for a wideband planar inverted F-antenna consisted of a main patch with stubs, an I-shaped patch, and a modified shorting strip. The proposed antenna covered GSM900, GPS, DCS1800, IMT2000, WLAN, and DMB services. Wang *et al*. introduced two novel printed inverted-F antenna (PIFA) related dual-band antennas for 2.45 and 5.25 GHz wireless local area network (WLAN) applications [Wang *et al*. (2007)]. One designed by spiraling the tail of the PIFA and the other is by modifying the feed structure of the PIFA into a coupling configuration. Seol *et al*. [Seol *et al*. (2007)] summarized the design of a novel broadband antenna with modified PIFA which covered GSM900, DCS, UMTS, and WiBro frequency bands of mobile applications. Modified PIFA was designed by embedding a planar inverted-L (PIL) patch in the planar inverted-F (PIF) patch. Additionally, a bent feed line is used to improve the impedance matching at the desired bandwidth. Chi and Wong presented a novel dual-band (GSM 900/1800) printed loop antenna comprised with an outer loop strip and an inner inverted-L strip connected to and enclosed by the outer loop strip [Chi and Wong (2007)]. Villanen *et al*. [Villanen *et al*. (2007)] proposed a novel internal coupling element-based antenna structure for quad-band mobile terminals. The antenna structure comprised of two non-resonant coupling elements, a multi-resonant matching circuitry. Ling *et al*. presented an on-package PIFA, consisting of a single folded metal plate for WLAN applications. Antenna directly on the package has the advantage of reducing feeder loss and the overall size of the circuitry [Ling *et al*. (2007)]. Li *et al*. [Li *et al*. (2007)] developed a very-low-profile (VLP) broadband planar antenna for DCS-1800 and IMT-2000 handsets. The VLP planar antenna consisted of an S-strip and a T-strip, which were separately printed on the two sides of a thin substrate. Mak *et al*. [Mak *et al*. (2007)] designed a compact reconfigurable antenna for GSM, DCS, PCS, UMTS, Bluetooth, and LAN bands. Li and Wong presented a new surface-mount loop antenna capable of quad-band operation covering the AMPS (Advanced Mobile Phone System), GSM, DCS, and PCS bands [Li and Wong (2007)]. The surface-mount loop antenna comprised of a meandered loop metal pattern and a central coupling stub to capacitively excite the meandered loop for quad band operation. Again in 2007, they also presented a printed loop-type antenna capable of penta-band operation in the mobile phone. Boyle and Steeneken [Boyle and Steeneken (2007)] designed a small microelectro mechanical systems (MEMS) switched planar inverted-F antenna capable of operating five cellular radio frequency bands. Wu and Wong [Wu and Wong (2007)] presented a printed pentaband compact uniplanar S-shaped monopole antenna for mobile phone application. Further, Lin and Wong [Lin and Wong (2007a)] proposed a new internal multiband mobile phone antenna formed by two printed monopole slots of different lengths cut at the edge of the system ground plane of the mobile phone. The antenna covered GSM850/GSM900/DCS/ PCS/UMTS bands and the 2.4-GHz WLAN band while in 2008, they [Lin and Wong (2007b)] presented new internal hybrid antenna formed by a printed monopole slot and a T-shaped metal-strip monopole for multiband operation. The monopole slot can generate a quarter- wavelength resonant mode at about 900 MHz for GSM850/900 operation. The monopole T-strip is quarter-wavelength resonant mode at about 1900 MHz to cover DCS/PCS operation.

Chan *et al*. [Chan *et al*. (2008)] introduced new wideband planar inverted-F antenna (PIFA) in which the shorting strip is modified into a meandering shape such that the antenna can have wideband characteristics. Later, Wong and Huang [Wong and Huang (2008)] presented a novel bandwidth-enhanced internal capacitively excited using a coupling feed planar inverted-F antenna (PIFA) for quad-band operation to cover GSM850/900 and DCS/PCS bands. Further, Wu and Wong [Wu and Wong (2008)] proposed a novel printed hybrid loop/monopole slot antenna for quad-band operation. The hybrid antenna was composed of a meandered loop antenna and a monopole slot antenna, and could generate two wide operating bands centered GSM850/900/DCS/PCS operation. Chang *et al*. [Chang *et al*. (2008)] introduced a surface-mount chip antenna integrated with the speaker in the mobile phone for GSM/DCS/PCS/UMTS multiband operation. The antenna was mounted on the top no-ground portion of the system circuit board of the mobile phone as an internal multiband antenna, and the speaker in the mobile phone can be inset into the chip base of the antenna. Soon after, Hua *et al*. [Hua *et al*. (2008)] discussed a compact multiband planar monopole antenna in which tuning techniques, including offset feed, etching meandered slot and cutting tuning inset, are applied to the radiator in order to maximise the operating frequency range of the antenna. The antenna covered the operating bands DCS/PCS/W-CDMA/2.4-/5-GHz WLANs/Bluetooth and WiMAX. Followed by Kim *et al*. [Kim *et al*. (2008)] studied the application of multiple folded radiators to independent frequency control of a compact tri-band planar inverted-F antenna (PIFA). Lin and Wong [Lin and Wong (2008)] presented an internal multiband loop antenna suitable for small size mobile device. Along the antenna loop strip, it is configured to have two symmetric meandered sections and a central widened section.

Lee *et al*. [Lee *et al*. (2008)] used low temperature co-fired ceramic (LTCC) technology to realize the dual band quarter wavelength helical antenna instead of the quarter wavelength monopole for achieving minimization of ceramic chip antenna. Further, Chen *et al*. [Chen *et al*. (2008)] presented a simple modified planar monopole antenna with two operating bands (890–970 MHz and 1670–2350 MHz) for multiband mobile systems. The antenna is composed of two inverted-L branches and an open stub for impedance tuning. A modified design can be easily achieved by narrowing the widths of the lower resonant branch and the open stub for the frequency. Thereafter, Wong and Tu [Wong and Tu (2008)] proposed an ultra-wideband coupled-fed loop antenna for pentaband operation in the folder-type mobile phone. The antenna composed of a loop strip and a monopole feed for enhancing the operating bandwidth of the antenna, followed by Chi and Wong's [Chi and Wong (2008)] a multiband folded loop chip antenna. The antenna has a simple metal pattern comprising a folded loop strip and a tuning pad for multiband operation. Soon after, Bhatti and Park [Bhatti and Park (2008)] proposed a low-profile octa-band monopole antenna for mobile phone applications in which multiple resonators in a compact configuration were used.

Hsu and Wong [Hsu and Wong (2009a)] presented a compact ceramic chip antenna capable of generating two wide operating bands at about 900 and 2000 MHz for covering GSM850/900/1800/1900/UMTS WWAN operations, followed by a chip antenna formed by using an FR4 chip base and a folded-loop metal pattern proposed [Hsu and Wong (2009b)]. The folded-loop metal pattern is embedded in two different layers inside the FR4 chip base to achieve a compact structure, and a coupling gap was introduced to successfully excite two wide operating bands at about 900 and 2000 MHz to cover GSM850/900/1800/1900/ UMTS, 2.4-GHz WLAN, and 2.5-GHz WiMAX operations. Further, Bhatti *et al.* [Bhatti *et al.* (2009)] proposed a low-profile internal monopole antenna for multi-standard mobile phones while Hsieh *et al.* [Hsieh *et al.* (2009)] presented a novel multiband internal antenna based on a combination of a loop-type antenna and a shorted monopole for GSM/GPS/DCS/ PCS/UMTS/Bluetooth/WLAN/WiFi/ WiMAX applications. Chi *et al.* [Chi *et al.* (2009)] proposed quad band inverted-F antenna for PDA applications. Soon after, Lee and Wong [Lee and Wong (2009)] reported a compact uniplanar coupled-fed PIFA which was formed by two coupled-fed PIFAs of different sizes, a longer radiating/coupling portion and a shorter radiating/coupling portion. The proposed antenna provides two wide operating bands at about 900 and 2000 MHz for covering GSM850/900/DCS/ PCS/UMTS/WLAN band operation. Further, Rhyu *et al.* [Rhyu *et al.* (2009)] proposed a hybrid antenna consisting of two PIFAs and an open slot antenna to cover GSM 850/900, DCS, PCS, and UMTS bands. Saidatul *et al.* [Saidatul *et al.* (2009)] presented a novel Fractal planar inverted F antenna (F-PIFA) based on the self affinity property for use in cellular phones to be operational at GSM, UMTS and HiperLAN bands. Chen *et al.* [Chen *et al.* (2009)] investigated a microstrip taper-fed compact printed monopole antenna by embedding two narrow slits into the rectangular-shaped radiating patch, a triple-band operation that covered the GSM, DCS, PCS and WLAN applications. Afterward, Cabedo *et al.* [Cabedo *et al.* (2009)] designed a multiband handset antenna combining a PIFA and multiple slots on a ground plane. The slots on the ground plane are used to tune the ground plane resonance at low frequencies and to act as parasitic radiators at high frequencies. A designed antenna covered GSM850, GSM900, DCS, PCS, UMTS and Bluetooth frequency bands. Sim *et al.* [Sim *et al.* (2009)] presented a novel design of a microstrip-fed planar antenna operating in GSM, DCS, PCS, WiBro, WLAN, WiMAX, GPS/GLONASS, and MSS bands. Thereafter, Chiu and Chi [Chiu and Chi (2009)] proposed a planar hexaband antenna that comprised of a dual-band inverted-F resonator and two parasitic elements to broaden the bandwidth. Further, Chen and Wong [Chen and Wong (2009)] developed wideband coupled-fed PIFA suitable for application in the clamshell mobile phone for achieving WWAN operation and meeting hearing-aid compatibility (HAC) standard ANSI C63.19-2007. The developed antenna was formed by two coupled strips (a longer one and a shorter one) capacitively fed by a common feeding strip. Ali and Kanj [Ali and Kanj (2009)] proposed two folding approaches of the monopole antenna. The first is in a three-dimensional manner and second is achieved by wrapping the antenna around the PCB. The antenna supports six frequency bands, GSM 800/900/1800/1900, UMTS, and Bluetooth. Soon after, Chu and Wong [Chu and Wong (2009)] designed a simple folded monopole slot antenna promising for penta-band clamshell mobile phone applications, followed by Kang and Wong's [Kang and Wong (2009)] proposed a simple and small size coupled fed uniplanar PIFA for multiband clamshell mobile phone. Thereafter, Chang and Wong [Chang and Wong (2009a)] presented a printed monopole embedded with a printed narrow strip as a distributed inductor for application in the mobile phone to achieve GSM850/900/1800/1900/UMTS penta-band WWAN operation.

In 2010, Liu *et al*. [Liu *et al*. (2010)] proposed a compact T-slit monopole antenna with slotted ground plane for penta-band operation. In addition, an inverted-L copper strip is soldered to the end edge of the monopole for extending the electrical length of the antenna for GSM band. Further, Wong and Chen [Wong and Chen (2010)] presented a printed single strip monopole using chip inductor capable of generating two wide operating bands at about 900 and 1900 MHz covering GSM850/900/1800/1900/ UMTS penta-band WWAN operation in the mobile phone. Thereafter, Lim *et al*. [Lim *et al*. (2010)] studied a reconfigurable planar inverted-F antenna using a switchable PIN-diode and a fine-tuning varactor for USPCS/WCDMA/m-WiMAX/WLAN applications. Selection of operating bands was achieved by switching the PIN-diode between radiators and tuning the varactor on an antenna's shorting line, followed by Du and Zhao's [Du and Zhao (2010)] novel internal quad-band PIFA for oval-shaped mobile phones. The obtained bandwidth covers GSM850, GSM900, DCS1800, and

PCS1900 bands. Sze and Wu [Sze and Wu (2010)] designed and constructed a meandered monopole PIFA with a combination of parasitic resonant element and an impedance-adjustment structure. Two wide impedance bands are generated by the designed antenna to support GSM 850, GSM 900, DCS, PCS, UMTS, and 2.4 GHz WLAN operations. Soon after, Liu *et al*. [Liu *et al*. (2010)] presented a small low profile dual wideband antenna formed by a monopole and an open-end slot embedded therein. Further, Oh *et al*. [Oh *et al*. (2010)] demonstrated a simple method of bandwidth enhancement for PIFA by making a multi-element PIFA. Later, Wong *et al*. [Wong *et al*. (2010)] developed a coupled-fed printed PIFA with a small footprint for eight-band operation covers LTE700/2300/2500, GSM850/900/1800/1900, and UMTS bands. The developed PIFA used only a single radiating strip which is short-circuited to the system ground plane through a long inductive shorting strip and is capacitively excited by a long coupling strip. The capacitive excitation leads to the generation of the $\lambda/8$ resonant mode at about 850 MHz and the higher order resonant modes at about 1900 MHz for the printed PIFA. The inductive shorting strip contributed additional inductance to achieve enhanced impedance matching for the excited 850 MHz band to achieve a dual-resonant behavior, which resulted in a wide lower band to cover the LTE700/GSM850/900 operation. A higher order resonant mode at about 2650 MHz is also contributed by the long inductive shorting strip. Later, Chiu and Chang [Chiu and Chang (2010a)] suggested a multiband meandered folded-loop antenna for smart phone application whereas folded dual-loop antenna was proposed by Ku *et al.*[Ku *et al.* (2010)] for GSM/DCS/PCS/UMTS applications. Ma *et al*. [Ma *et al*. (2010)] proposed a capacitive feed, composed of dual twisted lines, a shorting strip, and a parasitic loop antenna for GSM850/900/DCS/PCS/ UMTS/WiMAX/HIPERLAN2 operation. Soon after, Zhang *et al*. [Zhang *et al*. (2010)] achieved wide band characteristics by using meander structure, L-shaped slots in the ground plane and tapered feeding line a multiband planar monopole antenna. Later, Kang and Sung [Kang and Sung (2010)] proposed a compact hexaband PIFA constituted by a long radiator and a short radiator attached to the feed point and shorting pin. The long radiator served as the base radiator for the

PIFA, while the short radiator formed an independent resonance to cover GSM 900, DCS, PCS, UMTS, WiBro, and Bluetooth bands. Further, Chen and Lee [Chen and Lee (2010)] presented a meandered PDA antenna for GSM 900, DCS, PCS, UMTS, and WLAN applications while Chiu and Chang [Chiu and Chang (2010)] developed a multiband folded loop antenna in which a pair of rectangular tuning elements near the feed port are applied to adjust resonance modes to cover GSM850/GSM900/DCS/PCS/UMTS bands.

In 2011, small-size wideband monopole antenna closely coupled with a parasitic chip-inductor-loaded shorted strip for GSM1800/1900/UMTS, WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.5/3.5/5.5 GHz) operation in the slim mobile phone was presented by Wong and Lee [Wong and Lee (2011)], followed by, Wong *et al.*'s [Wong *et al.* (2011)] small-size on-board printed WWAN antenna to closely integrate with the surrounding ground plane in the mobile phone. The antenna is a coupled-fed loop antenna, which showed a simple structure of comprising a 0.25-wavelength loop strip capacitively coupled by a feeding strip. The antenna showed two wide operating bands to cover respectively the GSM850/900 and GSM1800/1900/ UMTS operations. Further, Kim *et al.* [Kim *et al.* (2011)] designed a small antenna with coupling feed structure and parasitic elements which supported the GSM 850/900, DCS,PCS frequency bands. The coupling feed structure provided wideband characteristics to PIFA. Soon after, Chen and Wong [Chen and Wong (2011a)] depicted an internal eight-band LTE/WWAN on-board printed antenna which meets the hearing air compatibility (HAC) specification of ANSI C63.19-2007 in the bar-type mobile phone. The antenna is a coupled-fed inverted-F antenna directly printed on the system circuit board of the mobile phone and could generate two wide operating bands (698–960/1710–2690 MHz) to respectively cover the LTE700/ GSM850/900 and GSM1800/1900/UMTS/LTE2300/2500 operation. Sim *et al.* [Sim *et al.* (2011a)] designed a compact size planar microstrip-fed monopole antenna for mobile handset. A hybrid technique of joining the horizontal section of a T-monopole to an open-loop back coupling strip and loading a pair of monopole slot into the ground plane was used to operate GSM, GPS, DCS, PCS, UMTS, WLAN bands.

Again in the same year, they [Sim *et al*. (2011b)] proposed a printed compact size folded inverted-F antenna with simple configuration for mobile handset. A narrow stub protruded from the printed shorting wall to cover GSM, PCS, DCS, WLAN bands. Thereafter, Peng *et al*. [Peng *et al*. (2011a)] communicated a novel penta-band antenna structure which comprised metal-wire-cutting bended monopole antenna (BMA) fed by mini-coaxial cable jointly with a thin printed ground-line to operate CDMA, GSM, DCS, PCS and WCDMA bands. Soon after, Chen and Peng [Chen and Peng (2011)] proposed a printed non-uniform meander line compact antenna consisted with perpendicular feed and open-stub structure, making it easy to operate in code-division multiple access CDMA, GSM, DCS, PCS, WCDMA. Thereafter, Chattha *et al*. [Chattha *et al*. (2011)] discussed three techniques of impedance bandwidth enhancement of PIFA, which are (i) changes in the widths of feed plate and shorting plate, (ii) addition of an inverted-L-shaped parasitic element and (iii) addition of a rectangular parasitic element. Wong *et al*. [Wong *et al*. (2011)] presented a simple printed monopole slot antenna for penta-band operation in the mobile handset whereas AbuTarboush *et al*. [AbuTarboush *et al*. (2011)] proposed a small ultra-thin PIFA consisted of a slotted radiator supported by shorting walls and a small ground plane to operate at 2.09, 3.74 and 5 GHz. Further, Peng *et al*. [Peng *et al*. (2011b)] designed an asymmetric T-type monopole antenna with a shorted-line operated in CDMA, GSM, DCS, PCS, WCDMA, and Bluetooth bands. Soon after, Chen and Wong [Chen and Wong (2011b)] presented a small-size wideband chip antenna for WWAN/LTE operation and close integration with nearby conducting elements in the mobile handset. The coupled-fed shorted strip contributed a wide resonant mode to cover the LTE700/GSM850/900 and the two-branch strip and the shorted strip together to cover the GSM1800/1900/UMTS/LTE2300/2500operation. Further, Chen *et al*. [Chen *et al*. (2011)] designed a meandered monopole antenna that operates a quarter wavelength impedance bandwidth at 900 MHz and its higher frequency modes at 1800 and 2400 MHz, can be used in the GSM, DCS, PCS, UMTS, WLAN applications. Afterward, Jeon *et al*. [Jeon *et al*. (2011)] realized an antenna by simply adding a branch line in the feed structure of the conventional

PIFA, which provided a very wide impedance bandwidth covering the LTE 13, GSM850, and GSM900 bands. Further, Sim and He [Sim and He (2011)] designed a compact microstrip-fed, double-folded PIFA with two wide open-ended radiating sections for mobile applications operating in the GSM/DCS/PCS/UMTS/WLAN and WiMAX bands.

In 2012, Lee and Su [Lee and Su (2012)] proposed a coupled-fed, short-circuited, T-monopole antenna, which comprised of two radiating arms for generating the lower and the upper operating bands and incorporated a conductive matching wire for good input matching therein. Proposed antenna covers GSM850/900/1800/1900, UMTS and WWAN bands. Further, Sim *et al*. [Sim *et al*. (2012a)] analyzed a uniplanar printed antenna by using an inverted L-shaped feeding mechanism and a meandered shorting strip to achieve dual-band operation with wideband characteristic. Here, the lower and higher operating bands were able to cover the LTE 700, GSM 850/900, DCS 1800, PCS 1900, UMTS, and LTE 2300 operations. Furthermore, in order to increase the bandwidth of the higher operating band to achieve LTE 2500 operation, an additional parasitic stub is attached to the feed line. Chen and Wong [Chen and Wong (2012)] demonstrated two techniques to achieve penta-band WWAN operation with low profile antenna. The first technique was to load a proper chip inductor at a proper position in the shorted strip monopole and second one was to use a band-stop matching circuit disposed to obtained desired 824–960 and 1710–2170 MHz bands. Thereafter, Liu *et al*. [Liu *et al*. (2012)] described a simple method for exiting a PIFA in order to achieve dual band operation. The conventional loop feed of a PIFA, formed by the feeding and shorting conductors, was modified by inserting a capacitor into the feeding conductor. The proposed feeding method provided a wide impedance bandwidth for 2.45 and 5.5 GHz WLAN applications.

Mahmoud *et al*. [Mahmoud *et al*. (2012)] presented a new design of hexa-band PIFA with T and S-slotted ground plane and S-etched slot on the radiation patch. The presented antenna was optimized using an efficient global hybrid optimization method combining bacterial swarm optimization and Nelder-Mead (BSO-NM) algorithm to cover a very important six service bands including

GSM900, GPS1575, DCS1800, PCS1900, ISM2450, and 4G5000 MHz with enhanced bandwidths. The BSO-NM algorithm in MATLAB code is linked to the CST Microwave studio software to simulate the antenna. Further, Sim *et al*. [Sim *et al*. (2012b)] designed a hybrid antenna with double layer structures that allow multiband operation in GSM, DCS, PCS, UMTS, and WLAN bands whereas Park and Sung [Park and Sung (2012)] presented a reconfigurable antenna using two PIN diodes for quad-band (GSM900, GSM1800, GSM1900 and UMTS) mobile handset applications. Soon after, Boldaji and Bialkowski [Boldaji and Bialkowski (2012)] depicted a compact hepta-band PIFA for portable devices while Wong and Lin [Wong and Lin (2012)] presented a novel internal handset antenna formed by a monopole slot and a monopole strip for the wireless wide area network (WWAN) operation in the 824–960 and 1710–2170 MHz bands. Later, Chen *et al*. [Chen *et al*. (2012)] proposed a coupled-fed planar printed antenna, formed by a double-branch feeding strip, a shorted coupling strip with two open-ended loops of different lengths, and a slotted ground structure consisting of two monopole slots. The antenna covered LTE700, GSM850/900, DCS, PCS, UMTS, LTE2300/2500 bands. Afterward, Sung [Sung (2012)] analyzed a reconfigurable antenna which was a combination of a PIFA mode and a loop mode. The property of this antenna was controlled by a pin diode switch. The proposed antenna covered GSM DCS, PCS, and WCDMA operations. Soon after, Ahn *et al*. [Ahn *et al*. (2012)] presented printed quad-band quasi-rectangular loop configuration and the shorted strip which covered the GSM900, DCS, PCS, and UMTS frequency bands. Further, Park and Lee [Park and Lee (2012)] described a novel and simple design film type inverted F-antenna for multiband operation. For multiband operation a modified meander line structure with L-shaped short pin was used. The proposed antenna covered GSM DCS, PCS, USPCS and WCDMA operations.

In 2013, Elsheakh and Abdallah [Elsheakh and Abdallah (2013)] proposed a design of low SAR planar monopole antenna for mobile communication applications in which an unequal arms monopole antenna with a meander strip in the other substrate side was used to cover GSM, DCS/PCS, WCDMA, UMTS, LTE, Wi-Fi, WiMax bands. Soon after, Ban *et al*. [Ban *et al*. (2013)] presented an on-board coupled-fed printed monopole with a distributed inductive shorted strip for seven-band operation covering the GSM850/900/1800/1900/UMTS2100/ LTE2300/2500 bands. Further, Li *et al*. [Li *et al*. (2013)] designed a novel PIFA using two open-end parallel slots in the ground plane for improvement the lower and the upper frequency operating band. Thus, quad-band frequency band 787-980 MHz, 1550-2065 MHz, 2250-2750 MHz, 5.04-5.84 GHz obtained. Later, Asghar *et al*. [Asghar *et al*. (2013)] proposed a multiband planar antenna for 4G devices comprised of a chopped circular radiator added with a meander line and an L-strip coupled element, which is an extension of the ground plane. The antenna covered wireless communication bands, such as LTE 750, GSM 850, GSM 900, DCS, UMTS-2110, Bluetooth, WLAN, WiMAX, and UWB. Afterward, Bujalance *et al*. [Bujalance *et al*. (2013)] analyzed the influence of handset components into the behavior of a handset antenna in a slotted ground plane in order to optimize the integration of the antenna into a handset device. Therefore, multiband handset antenna combining a planar spiral-shaped monopole and a slotted ground plane is used to study the influence of different components over the antenna performance. The antenna features a suitable behavior to operate in several mobile communication standards such as GSM850, GSM900, GSM1800, GSM1900, UMTS2100, LTE2100, LTE2300, Wi-Fi, and Bluetooth. The effect of a display, a speaker, and a battery has been investigated and recommendation rules are proposed in order to facilitate the integration of those components over the slotted ground plane without degrading the multiband performance. Lee and Sung [Lee and Sung (2013)] presented a compact, reconfigurable PIFA using a PIN diode to achieve LTE, GSM850, GSM900, DCS, PCS, and UMTS bands whereas Ban *et al*. [Ban *et al*. (2013)] proposed a coupled-fed antenna with two symmetrical printed meandered inductive strips as two distributed inductors for seven-band operation to cover the GSM850/900/1800/1900/UMTS2100/LTE2300/2500 bands. Later, Chang *et al*. [Chang *et al*. (2013)] depicted a simple printed monopole slot antenna with two parasitic shorted strips one is longer parasitic shorted strip and other is a shorter parasitic shorted strip for GSM850/900/1800/1900, and WCDMA penta-band wireless wide area network operations.

In 2014, Hsu and Chung [Hsu and Chung (2014)] communicated a compact multi-band antenna for 4 G mobile phone. The antenna composed with a straight coupled-fed microstrip line, a U-shaped slot, and a tapered open-end to generate four resonance modes, including two slot modes and two monopole modes. The antenna covered LTE Band 12 (698–742 MHz)/DCS (1710–1880 MHz)/PCS (1850–1990MHz)/UMTS (1920–2170 MHz)/LTE Band 40 (2300–2400 MHz)/Band 41 (2496–2690 MHz)/Band 42 (3400–3600 MHz)/Band 43 (3600–3800 MHz). Further, Ban *et al*. [Ban *et al*. (2014)] proposed, a small-size low-profile narrow-frame antenna for seven-band WWAN/LTE operations in the internal smart phone applications. Soon after, Lee and Sung [Lee and Sung (2014)] demonstrated hepta-band (GSM850/900/DCS/PCS/UMTS/LTE2300/2500) inverted –F antenna with independent resonance control for mobile handset applications. The antenna consisted of four radiating branches. Each branch operates at a quarter-wavelength mode as the fundamental resonant mode. Further, Park *et al*. [Park *et al*. (2014)] presented a magneto-dielectric handset antenna for LTE/WWAN/GPs applications. The antenna combined a coupled feed scheme and magneto-dielectric material for bandwidth enhancement. Later, Xie and Yang [Xie and Yang (2014)] designed eight-band printed antenna with T-shaped feeding line coupled with parasitic inverted-F structure. The antenna provided bandwidth to cover low band of LTE700/GSM850/GSM900 and high band of GSM1800/GSM1900/ UMTS2100 and LTE2300/2500. Chattha *et al*. [Chattha *et al*. (2014)] presented a simple planar inverted-E antenna (PIEA) which is a modified form of PIFA having two shorting plates instead of one. This antenna covered most of the frequency bands used in second generation (2G), third generation (3G), and fourth generation (4G) wireless applications. Further, Sheng and Di [Sheng and Di (2014)] proposed a compact antenna using S-shaped shorted strip and inverted L-shaped shorted strip for 4G mobile handset. The antenna covered LTE 700 (698–787 MHz), LTE 2300 (2305–2400 MHz), and LTE 2500 (2500–2690MHz) frequency bands. Soon after, Kim *et al*. [Kim *et al*.

(2014)] proposed T-monopole and capacitively coupled strip structure using a ferrite substrate for GSM/DCS/PCS/UMTS bands.

In 2015, Wang and Yang [Wang and Yang (2015)] presented a novel compact octaband printed internal antenna which was a combination of a monopole and a parasitic planar inverted-F antenna type of structure. The wide bandwidth at both lower and upper frequency band is achieved by integrating direct-fed monopole structure and coupled-fed PIFA structure. Thereafter, Lee *et al*. [Lee *et al*. (2015)] showed multiband operation antenna by controlling the magnetic coupling between the feed structure and antenna structure with a slot structure and inductor. Soon after, Huang and Wu [Huang and Wu (2015)] achieved two wide operating bands of 824–960 and 1710–2690 MHz, respectively by using a feeding strip and two radiating strips printed on the two sides of the no-ground substrate separately. Later, Wong and Wu (2015) [Wong and Wu (2015)] proposed dual opening slot (DOS) antennas for LTE/WWAN smart phone application. DOS antenna was configured into two open slot, first was longer and a second was shorter to generate multiple resonant modes. By further with the aid of wideband matching networks in the two feeds, the DOS antenna can provide two wide operating bands to cover the LTE/WWAN operation.

From the brief historical review, it is observed that a copious work has been carried out on the topic which is concentrated to the various aspects of the feeding, compactness, bandwidth enhancement, and frequency tunability techniques of IFA, PIFA, chip antenna, and planar monopole antennas for mobile communication application. Still there is a need to improve the overall performance of the planar monopole antenna to make it compact and to be used in 4 G mobile handset applications.

In view of the foregoing, author has endeavored to take up this topic for the study. Consequently, both simulation and experimental studies have been carried out the details of which embody the thesis. However, various configuration of planar monopole antennas are studied the details of which are given in the following chapter.