Considering High-Performance Near-Field Reader Antennas

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***Abstract*— An overview of the state-of-the-art of the antennas for ultra high frequency (UHF) near-field (NF) radio frequency identification (RFID) readers is presented. The specific requirements, design considerations, and design guidelines are addressed. Major types of designs reported in the scientific literature are illustrated and discussed.**

***Index Terms*—Antenna, near-field antenna, radio frequency identification (RFID), ultra high frequency (UHF), RFID reader, near-field region, segmented loop antenna, near-field coupling.**

I. Introduction

Radio Frequency Identification (RFID) is being widely used in supply chain and logistics applications for wireless identification, tracking and tracing of goods, with excellent performance for long-range interrogation of tagged pallets and cases (up to 4–6m, with passive tags). Item level tagging (ILT) has also been received a lot of attention, especially in pharmaceutical and retail industries. Low frequency (LF: 125 KHz–134 KHz) and high frequency (HF: 13.56 MHz) RFID systems have traditionally been used for ILT applications, where the radio frequency (RF) power from the reader is delivered to the passive tags by inductive coupling. Recently, the ultra high frequency (UHF: 840–960 MHz) near-field (NF) RFID systems have attracted an increasing attention because of the merits of the much higher reading speed and capability to detect a larger amount of tags (bulk reading). A UHF NF RFID system [1] is a valuable solution to implement a reliable short-range wireless link (up to a few tens of cm) for ILT applications. Since the tags can be made smaller, RFID-based applications can be extended to extremely small items (retail apparel, jewelry, drugs, rented apparel), as well as to a successful implementation of RFID-based storage spaces, smart conveyor belts and shopping carts.

A continuous effort has been made by the researchers to improve the performance of the UHF NF RFID systems. In this context, several studies have been conducted to analyze the propagation channel and the mutual coupling between the reader and tag antennas [2]-[5]. In this way, the guidelines on the tag and reader antennas design can be inferred to improve the tag detection [6]. Chen *et al.* [2] proposed an equation to estimate the coupling coefficient between two antennas placed within the other's NF region. Also, Fuschini *et al*. [3] investigated the main properties of a UHF NF RFID system by means of a theoretical electromagnetic analysis based on simple but representative radiating elements (*i.e*. loops and dipoles). Furthermore, Buffi *et al*. presented a numerical analysis of the near-field coupling between UHF RFID tags on the basis of the power transmission efficiency (PTE) parameter [4]. In [5], PTE measurements have been used to characterize commercial UHF RFID passive tags in both near-field and far-field regions. It is worth noting that specific metrics and testing methods are not yet unified or generally adopted. On the other hand, customers and producers are interested in comparing read range and inventory rate of different products, so tests standardization is receiving a large attention too [7].

Further, ad-hoc NF reader antennas have been investigated to enhance the UHF NF RFID system performance, while confining the electromagnetic field in an assigned limited volume close to the reader antenna. In this paper, an exhaustive review on the antennas for UHF NF RFID readers is presented. Their main features and design considerations are discussed in Section II. Then, several key designs presented in the open scientific literature are described and discussed in detail. They have been categorized as: loop antennas (Section III), leaky transmission-line antennas (Section IV), and resonant antennas /arrays (Section V). Finally, a discussion on reconfigurable antennas is carried out in Section VI, and concluding remarks are summarized in Section VII.

II. Design Considerations for UHF Near-Field RFID Reader Antennas

A passive near-field RFID system consists of two main components: the transponder, or tag, which is attached to the object to be identified; and the reader, which is used to interrogate the transponder (Fig. 1). The transponder is equipped with a chip where a few data can be stored. The power and data exchange between the tag and the reader is realized by means of magnetic or electric field coupling [8]. The distance from which a tag can be read is called read range, and it depends on the tag typology, reader antenna typology, reader output power, field polarization, and environmental scenario. Different from far-field RFID applications where the tags and reader antennas are designed to maximize the read range up to several meters, the UHF NF RFID systems is usually required to limit the read range up to few tens of centimeter in an interrogation zone, or detection volume, surrounding the RFID reader in which a tagged item must be detected (Fig. 1).

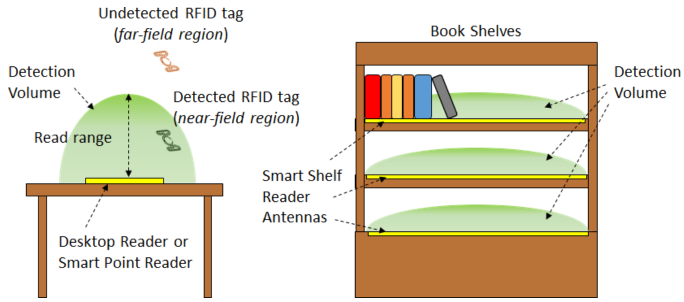


Fig. 1 Schematic representation of UHF NF RFID systems.

In a NF RFID system, the reader antenna and the tags can be coupled through either magnetic (inductive) or electric (capacitive) field when the tags are located in the reactive NF region of the reader antenna. Inductive coupling is preferred in most of the practical applications since the magnetic field is only affected by the objects with high magnetic permeability; the system is able to operate in close proximity to metals and liquids, and with crowded items in a close range. In contrast, capacitive coupling is hardly used in practical applications because the electric field is severely affected by objects with high dielectric permittivity and conductivity. The UHF tags used in the NF region can be generally detected by both inductive and capacitive coupling, differently from the HF systems that are based on the inductive coupling only. In this framework, efforts are being done to look for an antenna design parameter that can be calculated from reliable numerical simulations of the antenna near-field, which also relates to the reader detection performance. As an example [9], the active power density (amplitude of the real component of the Poynting vector) is proposed as a parameter to qualitatively predict the achievable reading performance of a desktop reader antenna through a numerical analysis of both the electric and magnetic vector fields in a selected volume close to the reader antenna.

Similar to any other wireless systems based on near-field coupling, the reader antenna is a key element to improve the system performance, when the output power of the reader is limited or the interference level must be maintained under a given threshold [10], [11]. A UHF NF RFID reader antenna is required to generate an as uniform/strong as possible field distribution in a confined interrogation zone to avoid tag detection failures. The required read range can vary from a few millimeters up to a few tens of centimeters, with an assigned reading rate, such as 100%. Moreover, the vector magnetic/electric field has not to exhibit a dominant component, as in most applications the tag orientation with respect to the reader antenna is unknown. Besides the issues of shape and size of the interrogation zone, field intensity and distribution, an UHF NF reader antenna should be cost effective and easy for system implementation as well. As for an example, the antenna for an RFID smart-shelf should be easily adaptable to different shelf sizes and types, and the field distribution must be controlled carefully to suppress the interference between the antennas in adjacent tiers of the shelves. Furthermore, the antenna for UHF NF RFID readers is usually required to be planar and low-profile design with smaller thickness as well.

Antennas that are suitable to implement an interrogation zone with surface area greater than $\lambda/2\times\lambda/2$ (λ being the free-space wavelength at UHF band) can be categorized as follows:

- ***Loop antennas***, such as segmented loop antennas and multi-loop antennas;
- ***Leaky transmission-line antennas***, based on microstrip, coplanar waveguide (CPW) or coplanar stripline (CPS) technology;
- ***Resonant antennas and arrays***, such as patches, slots, slotted patches, as well as arrays of above antennas.

Proper combinations of different antenna typologies have also been proposed to make a reader antenna suitable for both near-field and far-field applications. That is, the antenna is able to generate a strong and uniform field in proximity of its surface, while offer a not negligible far-field gain for farther tag detection. Also, metamaterials have been used to reduce the read range of a UHF reader antenna by utilizing an all-planar metamaterial wire grid to block the far-field radiation [12] and thereby obtain a spatially well-confined near-field detection region.

The reader antennas reviewed through the paper are summarized in Table I. The record of each layout presented in the open scientific literature contains the suggested applications, the operating frequency band, the antenna size, and the field components that have been considered during the antenna design process.

III. Loop Antennas

Single- and multi-turn solid-line loop antennas are the most commonly used in HF RFID readers because of their ability to generate strong magnetic field. However, at UHF band, a physically large loop required to offer an extended interrogation zone exhibits a weak field in its central portion, since the current along the loop experiences phase-inversions and current nulls. Some loops made of segmented lines (named as segmented loops) have been presented [13]-[33], where the current is kept almost constant and in-phase along the loop, even though the loop perimeter is larger than λ. Segmented loops can be configured using lumped capacitive elements [13], [14], distributed capacitors [16]-[19], coupled lines [20] and dash lines [21]-[26], or embedding phase-shifters into a solid-line loop [27]. Moreover, a segmented loop can also be implemented using dual dipoles [28]-[31] or dual open loops [32]-[33].

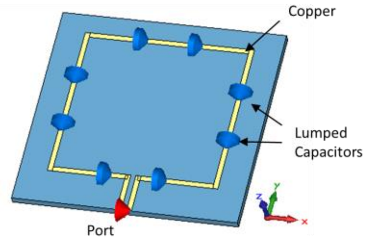
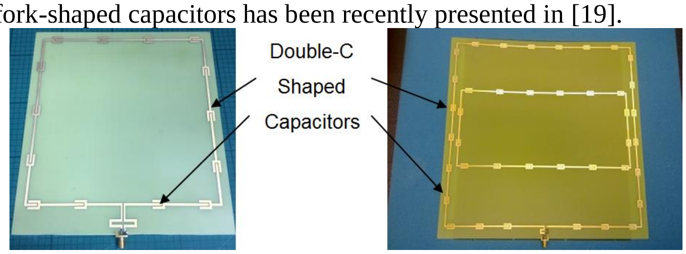


Fig. 2 Segmented loop antenna obtained by using lumped elements [13].

In the layout proposed by Dobkin *et al*. in 2007 [13], each segmented line section is made of a metal line section and a series-connected lumped capacitor (Fig. 2). However, the input impedance matching is awkward, since the radiation resistance is very small. Thus, a resistor is added to the matching circuit to achieve the required impedance matching. A similar capacitively loaded loop antenna is shown in [14], where a wideband balun is utilized to improve the input impedance matching. Simpler printed segmented loops can be realized by using distributed capacitors made with coupled lines (double-C shaped or fork-shaped capacitors) instead of lumped capacitors [16]-[19] (Fig. 3a). A square segmented loop with a perimeter of about 2λ has been designed in [16]. In [17]-[18], a parasitic segmented loop is added to the main loop in order to get an enhanced and uniform magnetic field distribution in the central portion of the larger main loop, so that the perimeter of interrogation zone of the dual-loop antenna can be extended up to 3λ (Fig. 3b). A dual-purpose near- and far-field segmented-line coil antenna with non-uniformly distributed turns and fork-shaped capacitors has been recently presented in [19].



(a) (b)

Fig. 3 Segmented loop antennas realized by means of double-C shaped capacitors: (a) single loop [16] and (b) dual-loop [17]-[18].

The dominant magnetic field of the segmented loop is perpendicular to the surface of the antenna, therefore maximum inductive coupling can be achieved when the loop-type tags are positioned parallel to the antenna surface. However, in some applications (as for example in a bookshelf) where the loop-type tag are positioned vertically oriented with respect to the reader antenna surface, the reader antenna is required to generate dominant magnetic field parallel to the antenna surface. Liu *et al.* [20] proposed a loop with a 16cm diameter, which is made of four large curved strips separated by four pairs of coupled stubs (Fig. 4). The stubs are designed to achieve antiphase currents on the opposite sides of the loop and improve the impedance matching.

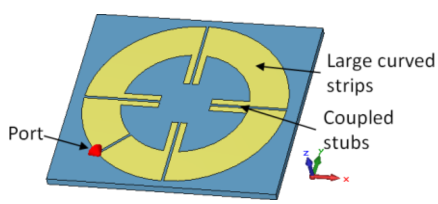
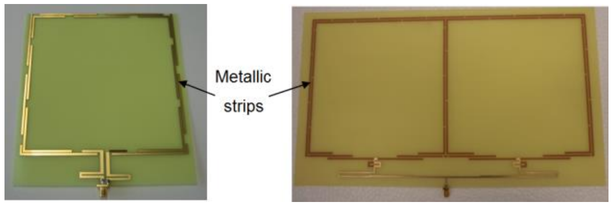


Fig. 4 Segmented loop antenna made of four large curved strips separated by four pairs of coupled stubs [20].

The segmented loop is also able to be configured by using coupled dash-line sections [21]-[23]. As shown in Fig. 5a, the segmented coupling line sections provide a small phase delay between the adjacent sections so that the current flowing along the segmented loop keeps in-phase. In [21], a coupled dash-line segmented loop is proposed by X. Qing *et al.*, which is characterized by a loop perimeter close to 2λ. A broadband segmented loop antenna with an interrogation zone of 15.4×15.4 cm^2 is presented in [22]. To enlarge the interrogation zone up to 30.8×15cm^2, Shi *et al.* propose a grid array as shown in Fig. 5b where two square segmented loops share a common edge [23].



(a) (b)

Fig. 5 Coupled dash-line segmented loop antennas: (a) single loop [21] and (b) grid array [23].

Two concentric segmented loops are proposed in [24] to enhance the magnetic field distribution. Dash-line segmented loop antennas have been used in various applications, such as an innovative animals tracking system [25] and a bracelet directly integrated into clothes [26]. As an additional modified loop structure (Fig. 6), in [27], stub phase shifters are embedded into a conventional solid-line loop (detection area equal to 16×16 cm^2). Other configurations including dual printed dipole structures, where each dipole is shorter than one wavelength [28]-[31], a dual-open-loop fed by a capacitive coupling port [32], and a multi-loop antenna [33] are reported as well.

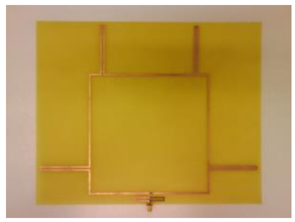


Fig. 6 A conventional solid-line loop with embedded stub phase shifters [27].

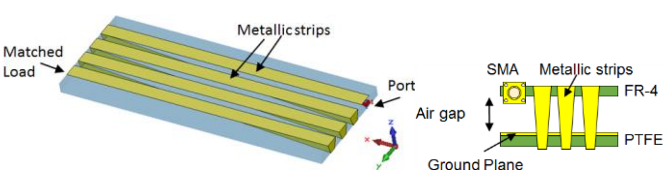
IV. Leaky Transmission-Line Antennas

In a leaky transmission-line antenna, the transmission line can be terminated with either a matched load (travelling wave current distribution) or a resistive load that can be varied to control the amount of energy of the reflected wave (stationary wave current pattern). Different printed-circuit technologies have been exploited: microstrip line [11], [34]-[38], coplanar stripline (CPSs) [39]-[41], and coplanar waveguide (CPWs) [42]-[44]. Generally, the leaky transmission-line antennas exhibit limited far-field radiation and therefore a very low far-field gain. In particular, the leaky transmission line overall length is typically smaller than three or four wavelengths at UHF band. Consequently, despite a not negligible attenuation constant, the power dissipated on the matched load is relatively high, so that a low far-field gain is naturally obtained. Moreover, the losses result in a larger impedance bandwidth and make the input impedance matching less sensitive to the presence of the tagged items in the antenna near-field region.

A. Microstrip line

In [34]-[35], a low-cost single microstrip line configuration is proposed for the RFID-based smart shelves to be used in bookstores and libraries. Moreover, a slightly-meandered version has been proposed to enhance the leakage of the less-dominant field components, and to extend the height of the tag-detection volume. A 50-cm-long straight microstrip line is also proposed in [36]. To excite all field components, a spiral-shape microstrip line is presented in [11], which is able to read tags over an interrogation zone of around 20×20cm^2. An enlarged interrogation zone of 30×40 cm^2 has been achieved by a 2×2 array, in which the spiral-shape elements are sequentially-fed.

A quite large planar printed antenna is proposed in [37], which can be easily adjusted in length and/or width to fit the shelf structure. The antenna is configured by cascading two layers of parallel microstrip lines (Fig. 7). The 50-Ω transmission line is terminated with a matched load and thus results in a wide impedance matching bandwidth. The top-layer microstrip lines are separated by the ground plane (the latter being located into the middle of the stacked structure) through a dielectric laminate and an air gap too. This air gap is used to generate a magnetic field on the top surface of the antenna. The currents on the parallel microstrip lines are in-phase, so that an almost uniform magnetic field is obtained on an interrogation zone as large as 74.7×17.6 cm^2. The use of transmission lines as UHF NF RFID reader antenna has also been investigated in [38], where a circular microstrip line with a limited ground plane is proposed. The overall antenna size is 5.65×5.9 cm^2.



(a) (b)

Fig. 7 Large planar printed transmission line antenna composed of two cascading layers of parallel microstrip lines [37]: (a) 3D view and (b) lateral view.

B. Coplanar Stripline

In [39], a 15×15 cm^2 spiral-shaped CPS is proposed (Fig. 8). The spiral shape, instead of a rectilinear one, is used to achieve a non-unidirectional magnetic field distribution. The distance between the two striplines can be used to control the magnetic field strength close to the surface as well as the antenna read range.

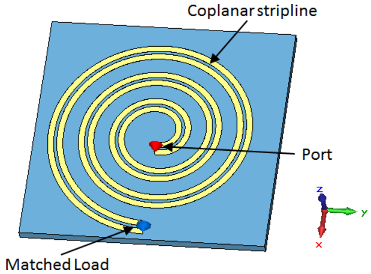


Fig. 8 Antenna with spiral-shape coplanar striplines [39].

In [40], Ren *et al.* present a CPS-based antenna for smart shelf applications. The CPS and multiple segmented lines fit an overall interrogation zone of 83.3×8 cm^2 (Fig. 9). The load resistance at the end of the CPS is equal to the characteristic impedance of the CPS. Since part of the currents travelling on the CPS are dissipated on the matched load, which reduces the antenna radiation efficiency and limits the far-field radiation. Furthermore, the antenna is able to produce a strong vertical magnetic field and improve the inductive coupling with the loop-like tags. Measurements show an interrogation zone of 240 cm^2 without any dead zone. A modified version is proposed in [41] for automatic goods inventory on the shelf, wherein five antennas are cascaded to one reader output.

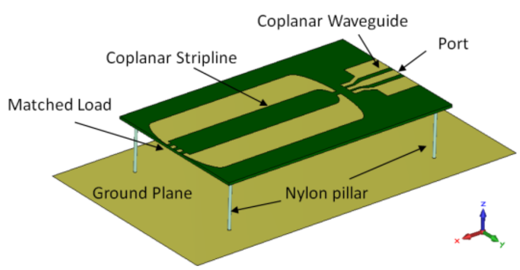
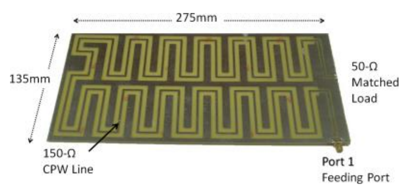


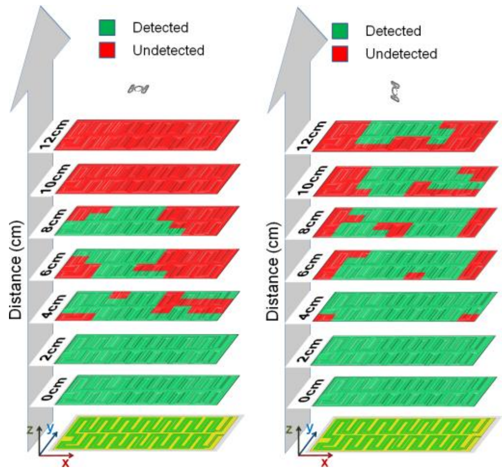
Fig. 9 Antenna based on CPS design [40].

C. Coplanar Waveguide

CPW NF antennas for UHF RFID applications are reported by Michel *et al.* [42]-[44]. In [42], an asymmetrical meandered CPW line based antenna (27.5×13.5 cm^2) is designed. It is referred as *Snake Antenna* in the following (Fig. 10a). To increase the field intensity above the antenna surface, a high characteristic impedance CPW line is designed. The meandered line is terminated with a matched load. The need for a matched load is twofold: it allows a travelling wave with no-stationary wave field distribution along the transmission line, and also reduces the antenna efficiency. Indeed, a low efficiency diminishes the far-field antenna gain, which is mandatory to avoid tag cross readings outside the assigned reader interrogation zone. Measurements with a reader output power set to 23dBm demonstrate that short-range tags can be detected up to 10 cm (Fig. 10b), and far-field tags can be read up to 50 cm [42]. An extension of the *Snake Antenna* is presented in [43], [44], where a 2×2 TWA array is designed (Fig. 11) to obtain a more confined and uniform field distribution close to the antenna surface (up to a few centimeters). In such a case, a typical far-field tag can be detected within 10cm [43].

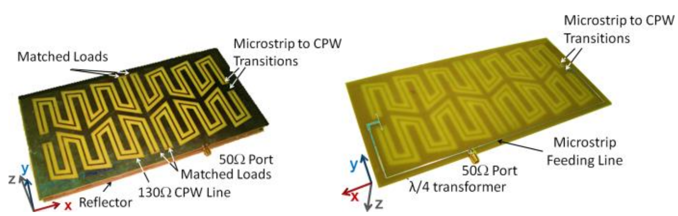


(a)



(b)

Fig. 10 The *Snake Antenna* based on CPW technology [42]: (a) prototype picture and (b) tag detection test results by setting an input power equal to 23dBm, with a short-range tag (UH113 by LAB-ID).



(a) (b)

Fig. 11 A 2×2 array of CPW Travelling Wave Antennas [43]: (a) top and (b) bottom view of the antenna prototype.

V. Resonant Antennas and Arrays

The size of a resonant antenna is strictly related to the operating frequency. On the other hand, miniaturization techniques have been employed to reduce the antenna size, allowing the radiating element to be embedded in commercial UHF RFID readers [45]-[47]. A number of layouts provide a strong magnetic field by using two out-of-phase currents [48]-[54]. To cover larger interrogation zone with resonant antenna configuration, an antenna array is a mandatory solution [55]-[63]. Fragment-type wire antennas have been recently proposed because the distribution of fragmented wires in an electrically-large area can be optimized to counterpoise the magnetic fields generated by non-uniform current distribution [64].

A. *Modified loop/dipole antennas*

A two-layered antenna (6.8×6.8×1.9 cm^3) made of two quasi-half-loops is proposed in [45] to generate a strong and even magnetic field (Fig. 12). Due to the presence of the matched load, a low gain of -10dBi and a broad operating bandwidth are achieved. In [46], a 15×15 cm^2 planar resonant antenna is proposed to maximize the magnetic field intensity toward the direction perpendicular to the antenna surface. The antenna is composed of a planar loop with a stub line, whose strength and phase of the surface current is controlled by length and thickness of the stub line. Also, a satisfactory good impedance matching is accomplished by parallel and series inductances located near the feeding line.

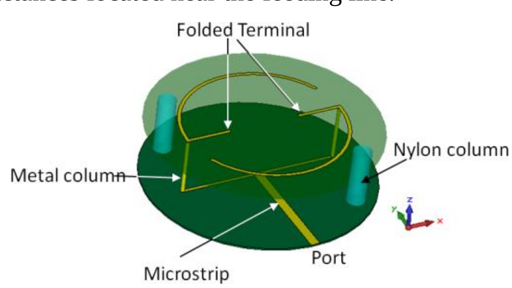
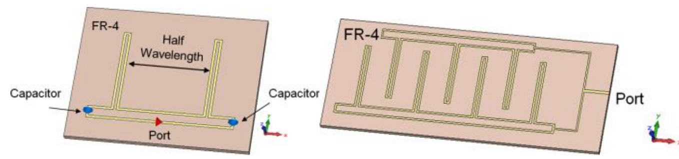


Fig. 12 Two-layered antenna structure using two quasi-half-loops [45].

B. *Oppositely-Directed Currents*

Two closely-spaced oppositely-directed (*i.e.* out-of-phase) currents (ODCs) are able to generate a strong and uniform magnetic field over a relatively large interrogation zone, mainly for the magnetic field component perpendicular to the antenna surface. Such an idea has been used in [48] to design antennas suitable for RFID-based smart shelves. In [48], the antenna is made of a symmetrical inverted-L dipole with a parasitic patch. In [49], two patches are series-fed by a microstrip line through a capacitive coupling. In all above realizations, the interrogation zone is about 30×30cm^2. A printed folded dipole is proposed in [50], based on a couple of ODCs. The antenna is printed on a piece of 20×32 cm^2 FR-4 substrate.

It is worth noting that for antennas based on the ODCs concept, the magnetic field component perpendicular to the antenna surface may experience dead zones since the magnetic field right above the current is in parallel with the antenna surface [51]. Thus, in [51] the two elements are put together in an interleaved configuration and fed with different phases (Fig. 13), so that the dead zones change position and distribution. The variable-distance ODCs concept (VDODC) is introduced in [52], where a 9×9 cm^2 fractal protruded tapered slot (FPTS) antenna is proposed.



(a) (b)

Fig. 13 Printed folded dipole based on the ODCs concept: (a) single element [50] and (b) double interleaved element [51].

In [53], an antenna made of a set of parallel printed open-ended transmission lines is designed to be installed below a chip tray, for casino chip management. The basic element of the antenna looks like a printed two-conductor transmission line. Each conductor is printed on one side of a dielectric laminate and is made of a conventional rectilinear strip, which is periodically loaded with transverse stubs. The two conductors lie on the opposite sides of the dielectric laminate and, differently from conventional printed transmission lines, they are slightly shifted from each other. The authors state that such a structure can generate both electric and magnetic field components, in both the directions parallel to the antenna surface, so that it is suitable for RFID smart table applications where the tags can be arbitrarily oriented and of any category. An interrogation zone of 20×19 cm^2 is obtained. While the antenna comes out from a travelling wave concept, its reflection coefficient exhibits a typical resonant aspect since each printed transmission line is open-ended (the achieved percentage bandwidth is less than 1%). Similarly, in [54], [55] the out-phase currents on two microstrip meander lines are induced through a phase shifter. To expand the bandwidth of the antenna, in [56], a Wilkinson power divider and a phase shifter are used, which results in the simulated $|S_{11}|$ lower than -27dB in the entire UHF RFID band (860 MHz -960 MHz).

C. Arrays of Resonant Antenna and Transmission-Line

Combinations of transmission line and resonant antenna are proposed in [57]-[62], and hereafter named as *resonant transmission-line antennas*. The main component is still a transmission line but the latter is primarily used to feed an array of radiating elements, as for example an array of patches or slots. Differently from the leaky transmission-line type reader antennas, the resonant transmission-line antennas are usually with a small impedance bandwidth since the transmission lines are not terminated with a matched load.

Printed dipole arrays serially fed by a microstrip transmission line are proposed in [57]-[60]. Andrenko *et al.* [57]-[58] proposes a planar antenna based on the electromagnetic coupling between an open-ended microstrip line and periodic metal strips radiating in-phase (Fig. 14). A linear array of printed orthogonal dipoles is also designed by Boursianis *et al*. in [59], for searching misplaced tagged items in a smart shelf. Specifically, in each dipole pair, two different lengths are considered to broaden the bandwidth. Moreover, a meandered microstrip line is suitable to serially feed the double dipoles with less than one wavelength inter-element distance.

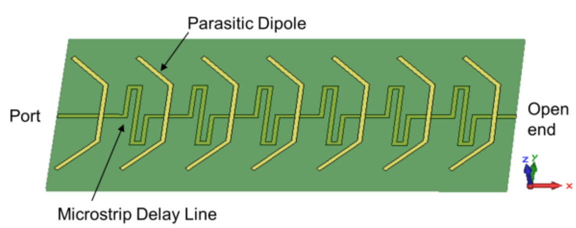


Fig. 14 Array of printed dipoles electromagnetically coupled to an open-ended microstrip line [58].

A similar approach is used in [60], where a printed rectilinear feed line is terminated with a resistive load whose value can be used to control the standing wave ratio as well as the antenna efficiency (Fig. 15). A good reading performance is expected where reflected and incident waves sum in-phase. To avoid a poor reading rate at those points along the line corresponding to minima of the field stationary pattern, a stacked structure has been proposed where a meander line is positioned at 3mm above the feeding line. The current excited on the meander line increases the field homogeneity on the antenna surface and also generates current components in a direction perpendicular to that of the current flowing on the rectilinear feed line. A prototype is tested in a book shelf. It is shown that the received signal strength indicator (RSSI) values associated to tags attached to the books are in good agreement with normalized magnetic field measurements made on the antenna surface by a small loop probe. The antenna is 80 cm long and 10 cm wide, and exhibits a 60-MHz impedance bandwidth (return loss larger than 10dB) with tolerable variations when changing the number of books located on the shelf. The stacked structure is immersed in a 2 cm thick metallic cavity

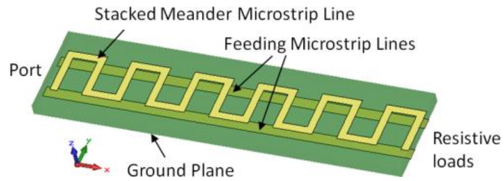


Fig. 15 Printed rectilinear feed line terminated with a resistive load [60]. A stacked meander line is added to improve the field homogeneity.

In [61], a linear array of electrically long slots is fed through a set of parallel open-ended microstrip lines (series-fed array), the la+tter being fed through a conventional corporate feeding network (Fig. 16). The antenna is composed of a dielectric substrate with a ground plane where a number of long slot pairs are etched. The slots are 320 mm long and the distance between two slots is 3 mm, while the distance between two slot pairs is 9 cm [61]. The feeding microstrip line is printed on the other side of the substrate. Since the microstrip lines are open ended, a stationary pattern of the current is established along the line. Slots are coupled to the microstrip line at the current peak positions. All slot pairs are excited in-phase and with almost equal amplitude to achieve a uniform magnetic field distribution over the antenna surface with no dead zones. The authors state that a uniform field distribution with no nulls is obtained within an interrogation zone of 410×320 mm^2, for an antenna prototype embedded in a shelf.

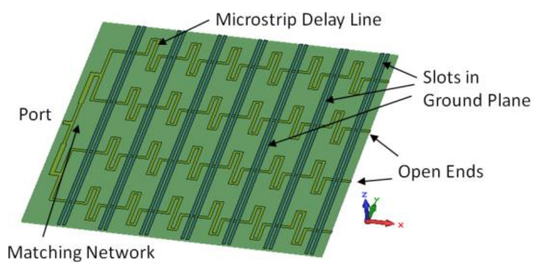


Fig. 16 Linear array of electrically long slots fed through a set of parallel open-ended microstrip lines [61].

In [62]-[63], multiple pairs of folded dipole antennas are printed on the same plane of the feeding microstrip line. The latter is ended on an open-circuit, so a voltage-current standing wave is produced. Each pair of folded dipoles is coupled to the feeding line in such a way to radiate a circularly polarized field.

VI. Antenna Reconfigurability

Recently, reconfigurable antennas for UHF RFID readers have been proposed, by using reconfigurable media such as plasma [65] or lumped elements such as MEMS or RF switches [66]-[67] and varactor diodes [68]. In near-field applications, reconfigurable antennas can make the UHF NF RFID systems adjustable to various scenarios, as for example, different material properties of the tagged objects, or different size and shape of the required interrogation zone. Moreover, reconfigurable antennas that easily change the interrogation volume properties (*e.g.* interrogation area, field strength, field decay rate) among a number of configurations can significantly increase the read rate. Indeed, the analysis of UHF NF RFID reader antennas is often focused on the electric field distribution, which is reasonable for dipole-like tags detection [69]-[70]; on the other hand, there are other tags that are more sensitive to the magnetic fields (loop-like tags), or equally sensitive to the two field components.

In [71], a reconfigurable antenna based on planar blocks of parasitic meandered dipoles is proposed to fit the antenna into a specific smart shelf. These planar blocks also allow the antenna to be integrated into different supports. Results shown in [71] demonstrate that the proposed antenna can be configured to present a very large interrogation zone up 76 × 42 cm^2 (15 blocks configuration).

Reconfigurability can also be exploited to extend or reduce the detection volume size, and compensate for the field attenuation due to the presence of items made of different materials. As an example, in [68] a reconfigurable-pattern passive ETSI UHF (865–868 MHz) reader loop antenna for RFID applications is presented. Specifically, the antenna is loaded by a left-handed ladder network composed of four unit cells which consist of lumped capacitors and inductors. Using varactor diodes, the antenna operation frequency and radiation properties can be modified, making the antenna suitable for either near-field or far-field applications.

To obtain a spatially-reconfigurable interrogation zone for smart-shelf applications, Andrenko [66] proposes to add a set of RF switches to the array of printed dipoles described in [57], [58], so altering the length of the meander microstrip line and thus changing the phase distribution between the radiating elements. In [72], a doubled-gain antenna design consists of a planar loop with a power dividing network that can excite the odd- and even-mode currents along the loop wires. The excitation of the oddand even-mode currents allows providing an antenna gain two times greater than that of a single loop or dipole and thus extends the read range.

Some of the authors of this paper proposed the modular antenna concept [10]. To maximize the electromagnetic field in a confined volume within the antenna NF region (namely, in both the reactive and radiative near-field regions), a travelling wave antenna is combined with a low-gain resonating antenna, which share the surface of the desktop reader antenna. The travelling wave antenna covers the reactive near-field region, with almost uniform electric and magnetic fields, up to a few centimeters from the antenna surface. The low-gain resonating antenna is used to cover the radiative near-field region up to a few tens of centimeters from the antenna surface. A specific design of such a modular antenna is presented in [73]-[74]. A 50-Ω coaxial cable feeds a spiral shaped microstrip transmission line at its center, which in turn series-feeds a coplanar array of two miniaturized square patches (Fig. 17). Through a switch, the spiral microstrip line can be either connected to the patch array or terminated with a matched load. The latter configuration ensures a strong and uniform field distribution in a small volume just above the antenna surface, which is high desirable for tag writing operations or single-tag readings. On the other hand, the combination of the travelling wave antenna and the patch array is effective to improve the tag detection up to few decimeter from the antenna surface, even in presence of stacks of tags (where the detrimental effects of the mutual coupling between tags are not negligible).

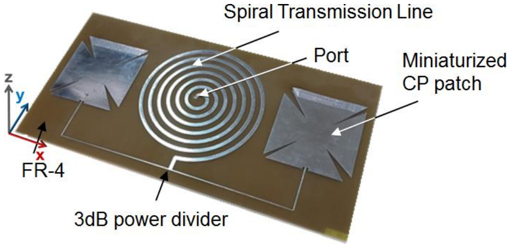
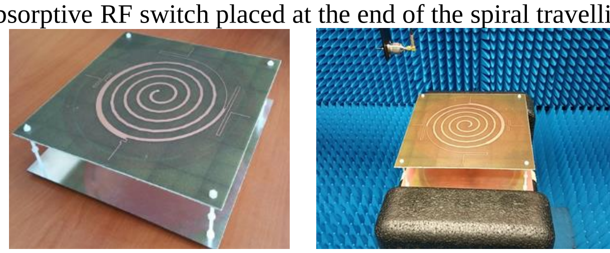


Fig. 17 *Modular Antenna* prototype consisting in a spiral-shaped traveling wave antenna that series-feeds a 2×1 array of miniaturized circularly-polarized patches [73]-[74].

A scalable version of the modular antenna concept is presented in [75]. Specifically, the proposed modular antenna consists of a spiral-shaped microstrip transmission line which serially-feeds a circularly-polarized ring slot resonant antenna. Thus, to make the antenna scalable, the microstrip stub is elongated beyond the ring slot to cover an arbitrarily larger area. Recently, a similar reconfigurable antenna (250×250 mm^2 wide) has been proposed by Michel *et al.* in [64], where the ring slot antenna is substituted with an array of four resonating slots connected in series to the travelling wave antenna through a printed matching/delay network as shown in Fig. 18. The electromagnetic field distribution generated by the overall antenna can be controlled and shaped through an absorptive RF switch placed at the end of the spiral travelling wave antenna.



(a) (b)

Fig. 18 (a) Fabricated prototype of the Reconfigurable Modular Antenna presented in [64] and (b) measurement setup for the near-field measurements.

VII. Conclusion

The increasing UHF NF RFID applications and the need for size-scalable reader antennas that can be used in various scenarios (RFID-based smart shelves and drawers, desktop readers) have motivated researchers to look for high-performance NF antennas, among the low-cost and low-profile layouts. Differently from the far-field RFID reader antennas, the considerations of UHF NF reader antennas focus on the electric and magnetic field distribution in the interrogation zone and the vector properties of each field component with respect to the potential tag orientation.

In this paper, the antenna solutions proposed by the scientific community have been carefully reviewed and compared in terms of operating principle, size and operating frequency bands. Specifically, a possible classification has been proposed based on the antenna operating principle, giving to the reader a quite large vision on the state-of-the-art of UHF NF RFID antennas. Among the most recent developments, it is worth mentioning that the utilization of reconfigurable antennas to shape the electric/magnetic near-field distribution features great potential for RFID applications.

Table I

Summary of Antennas for Near-Field UHF RFID Desktop Readers Considered in this Survey(*)

*The last column shows the field components that have been optimized during the design process (it is assumed that the antenna surface is on the *xy*-plane, while the *z*-axis is orthogonal to the antenna).

Ref.	Application	Operating Band	Size	Field
		Loop-like Resonant Antennas		
[13]	n.a.	890-930	Ø=100mm	n.a.
[14]	NF reader	873–933 MHz	Ø=100mm	H
[16]	NF reader	790–1000 MHz	158×158 mm^2	H_z
[17]	NF reader	800–1040 MHz	275×275 mm^2	H_z
[18]	NF reader	845–928 MHz	270×277 mm^2	H_z
[19]	NF reader	832–998 MHz	150×150 mm^2	H_z
[20]	NF reader	840–1300 MHz	170×170 mm^2	H
[21]	NF reader	800–1040 MHz	160×180 mm^2	H
[22]	NF reader	840–960 MHz	175×180 mm^2	H_z
[23]	NF reader	790–1040 MHz	318×182 mm^2	H_z
[24]	NF reader	920–925 MHz	139×161 mm+	H_x, H_y, H_z
[25]	NF reader	n.a.	100×115 mm^2	H
[26]	Bracialet	825–900 MHz	Ø=80mm	H
[27]	NF reader	840–960 MHz	306×249 mm^2	H_z
[28]	NF reader	750–970 MHz	80×70×30 mm^3	H
[29]	NF reader	814–1050 MHz	170×170 mm^2	H_z
[30]	NF reader	887–938 MHz	180×180 mm^2	H_z
[31]	RFID readers	840–845 MHz	96×96 mm^2	H_z
[32]	NF reader	888–932 MHz	60×60 mm^2	H_z
[33]	NF reader	n.a.	10×11 mm^2	n.a.
Ref.	**Application**	**Operating Band**	**Size**	**Field**
		Transmission Line Antennas		
[34] [35]	shelves, point readers, or conveyor belts	860–920 MHz	100×30 mm^2	E_x, E_y, E_z
[36]	NF reader	> 800–1000 MHz	60×40 mm^2	E_x, E_y, E_z
[37]	NF reader	> 800–1000 MHz	747×176 mm^2	H
[38]	NF reader	200–1800 MHz	56,5×59 mm^2	E,H,H_z
[39]	NF reader	820–1170 MHz	150×150mm^2	H
[40][41]	NF reader	800–1000 MHz	882×80 mm^2	H_z, H
[42]	desktop reader	> 850–950 MHz	275×136 mm^2	H_x, H_y
[43][44]	desktop reader	> 800–1000	275×136 mm^2	E, H
Ref.	**Application**	**Operating Band**	**Size**	**Field**
		Resonant Antennas and Arrays		
[45]	NF reader	826–950 MHz	Ø=68mm	H
[46]	UHF RFID readers	936–942 MHz	150×150×25 mm^3	H
[47]	NF reader	900–950 MHz	108×72×0.8 mm^3	n.a.
[48][49]	smart shelf	900–950 MHz	30×30 mm^2	H_z
[50]	NF reader	826–853 MHz	200×320 mm^2	H_z
[51]	NF reader	894–946MHz	640×240 mm^2	H_z
[52]	NF reader	852–953 MHz	90×90 mm^2	H
[53]	smart table for casino chips	908.5–914 MHz	95×240 mm^2	E, H
[54][55]	NF reader	914-929 MHz	200×480 mm^2	H_z
[56]	NF reader	> 200–1500 MHz	647.5×200 mm^2	n.a.
[57][58]	smart shelf	910–936 MHz	200×550 mm^2	E
[59]	smart shelf	865–930 MHz	400×2000 mm^2	E
[60]	smart shelf	n.s.	100×880 mm^2	H
[61]	smart shelf	905–921 MHz	410×320 mm^2	E_x, E_y
[62]-[63]	retail applications	910–950 MHz	560×220 mm^2	E_x, E_y
[64]	NF reader	880–945 MHz	350×350 mm^2	H_z
Ref.	**Application**	**Operating Band**	**Size**	**Field**
		Reconfigurable Near-field Antennas		
[69][70]	smart point reader	> 800–905 MHz	275×135 mm^2	E_x, E_y
[71]	NF reader	> 865–868 MHz	2000×280 mm^2	H_z
[68]	UHF readers	865–868 MHz	72.3×72.3 mm^2	H_z
[66]	smart shelf	902–928 MHz	730×200 mm^2	E_y
[72]	UHF readers	900–940 MHz	160×55 mm3	n.a.
[73][74]	desktop reader	> 850–880MHz	275×135 mm^2	H_x, H_y, H_z
[75]	desktop reader	> 850–960 MHz	275×135 mm^2	H

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