Gain-Optimized Self-Resonant Meander Line Antennas for RFID Applications

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***Abstract*—New meander line antennas with improved gain are proposed as low-profile self-resonant tags for application in passive radio frequency identification. Antenna shape and size is optimized by genetic algorithm taking into account the conductor losses. Examples are presented for application at 869 MHz with antennas of different materials and sizes.**

***Index Terms*—Genetic algorithms, miniaturized antenna, small antenna, transponders.**

I. Introduction

RADIO frequency identification (RFID) of objects and people and remote control of devices has become very popular in logistics, inventory management and bio-engineering applications [1]. Data are contactless transferred to a local querying system (reader) from a remote transponder (tag) including the antenna and a microchip transmitter. A suitable antenna for the tag must have low cost, low profile, and especially small size, whereas the bandwidth requirement (a few kilohertz) is less critical. In passive tag systems, the querying signal coming from the reader must have enough power to activate the tag microchip, perform data processing and transmit back a modulated string up to the required reading range (typically 0.3–1 m). Since the maximum effective isotropic radiated power (EIRP) of the reader is constrained to local regulations, high-gain tags are required to increase the reading range. Additionally, to simplify the matching network and obtain low-cost tags, the antenna should be self resonant.

In the ultra-high frequency (UHF) band, especially below 1 GHz, meander line antennas (MLA) are an attractive choice for the purpose of reducing the tag sizes. As proposed in [2], folding the elements in a meander produces a wire configuration with both capacitive and inductive reactance, which mutually cancel. Resonances are therefore produced at much lower frequencies than in the case of straight wire antenna of the same height at the expense of narrow bandwidth and low gain, especially when the antenna surface needs to be contained in a few centimeter-side square (less than $4 \times 4\ \mathrm{cm}^2$ to label small objects).

This paper discusses the design of *gain*-optimized MLA by means of genetic algorithms (GA) and investigates on the influence of the wire conductivity on the optimized shape of the antenna. Following preliminary results in [3], it will be shown that, for a fixed height, a standard MLA with regular meanders does not exhibit the optimum gain especially when the conductor losses can not be neglected and that the GA-optimized shapes with lossless wires are greatly different from the optimized antenna involving real conductors. It will be also proved that the optimized MLA shape converges to a top-loaded dipole as the available height increases.

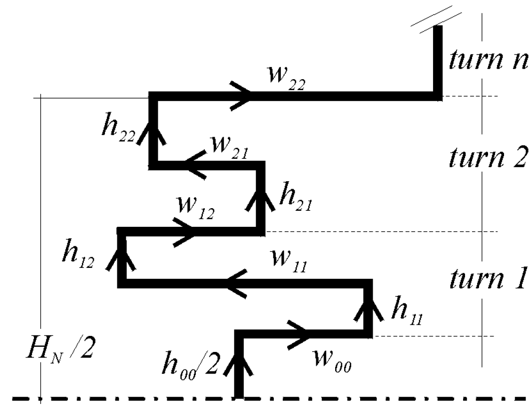

Fig. 1. Scheme for nonuniform MLA_N with indication of parameters to be optimized. Only half antenna is visible.

II. Evolutionary Design of MLAs

With reference to Fig. 1, the parameters of a symmetric rectangular MLA_N are: the number N of turns, the length of the horizontal (w_{n1} and w_{n2}) and vertical (h_{n1} and h_{n2}) segments of the nth turn and the length of the central segments w_{00} and h_{00}. The commonly used configuration is the *uniform MLA* (U-MLA), which is a particular geometry described by only three parameters—N, $w_{ni} = w_{00}$, and $h_{ni} = h_{00}$—hereafter denoted as U-$\mathrm{MLA}_N(h_{00}, w_{00})$. The most general symmetrical *nonuniform* $\mathrm{MLA}_N(h_{ni}, w_{ni})$ is singled out by $4N+3$ parameters.

Design curves for self-resonant U-MLA_N can be easily obtained by setting the height H and then iteratively tuning the width $W = w_{00}$ to have the antenna at resonance. For example, Fig. 2 shows the tuning curves for copper wire U-MLAs where the method of moments [4] has been used for antenna modeling. As expected, higher order antennas (N > 1) have a smaller resonant width since the wire is folded along a greater number of turns within a small area. Moreover, the gain becomes lower for increasing N but approaches the gain of a straight dipole as the height increases.

Up to the first antenna resonance, the currents on the adjacent horizontal segments of the MLA have opposite phase. These transmission line currents do not give valuable contribution

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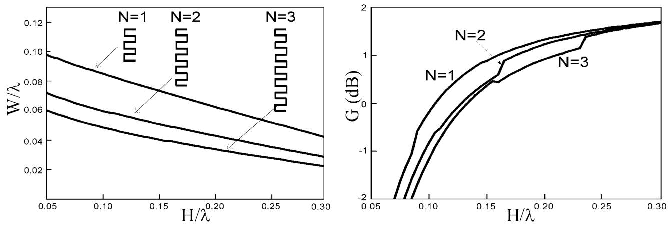


Fig. 2. (a) Design curve for small copper U-MLA. (b) Maximum gain for resonant U-MLA versus the height H for different meanders.

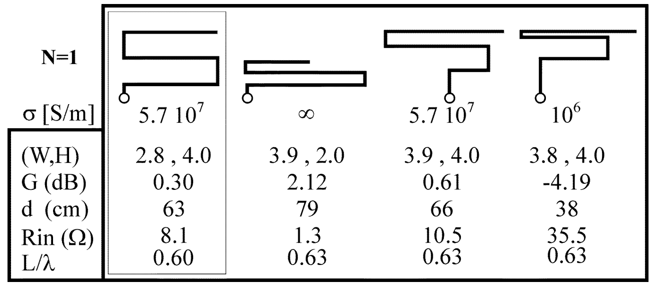


Fig. 3. Optimization results at 869 MHz, for MLA_1, with sizes (in cm) not exceeding $H_{\max} = W_{\max} = 4$ cm. Copper U-MLA in the first column. The circles indicate the source points.

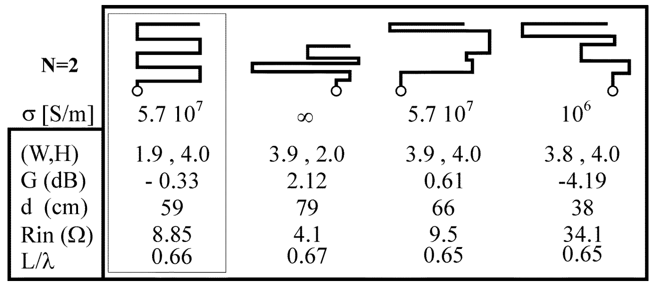


Fig. 4. Optimization results (sizes in cm) at 869 MHz for MLA_2.

to the radiated power, but they nevertheless produce losses. In particular, a lot of power is wasted close to the antenna center, where the current reaches highest values. The radiation resistance is therefore mainly affected by the vertical segments and, hence, as shown in [5], by the antenna total vertical height relative to the resonant wavelength. On the contrary, the loss resistance is primarily determined by the wire diameter and by the total wire length. For a fixed maximum available area $(W_{\max} \times H_{\max})$, the optimum gain is therefore expected to be achieved with that antenna design having the highest radiation resistance and the smallest total wire length. The above optimization problem, involving a tradeoff between miniaturization with self resonance (long wire length) and loss minimization (short wire length), requires all the vertical and horizontal segments to be independently designed and can be efficiently handled by the GA approach that has been widely used as an electromagnetic design tool [6]. For the actual problem, the length of each segment of the MLA is encoded into 7 bits and each antenna is solved by the method of moment, provided that the minimum segment length is $h_{\min} \geq (6/1000)\lambda$, which still permits to perform stable electromagnetic analysis. For each pth antenna of the GA population at the kth generation, the following fitness function is then evaluated:

$$f_p^{(k)}(G_p, H_p, X_p) = r_1 \frac{G_p}{G_0} + r_2 \frac{H_p}{H_{\max}} + r_3 \frac{X_0}{|X_p| + X_0} \quad (1)$$

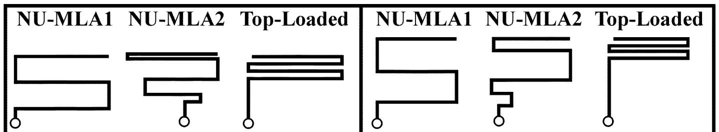
where G_p, H_p, X_p are the pth antenna height, maximum gain and input reactance, respectively. Parameters have been chosen as: $r_1 + r_2 + r_3 = 10$, $\mathrm{G}_0 = 1.63$ (maximum gain of half-wavelength perfect conductor dipole), $X_0 = 1\ \Omega$. The fitness function converges to $f_p = 10$ as the antenna gain equals G_0, the height equals $H_{\max}$ and the antenna is at resonance.

III. MLA for 869-MHz Applications

Some numerical experiments are reported at 869 MHz (a typical European frequency for RFID devices) for 0.1 mm wire MLA. A first optimized design set refers to antennas with maximum allowed size $W_{\max}$, $H_{\max} \leq 4\ cm(0.11\lambda)$, typical of book barcodes. The following wire conductivities have been considered: $\sigma = \infty$ (perfect electric conductor), $\sigma = 5.76 \cdot 10^7$ S/m (good conductor: copper) and $\sigma = 10^6$ S/m (poor conductor: a metallo-organic conducting ink [7]). A relevant parameter for these antennas is the activation range $d = \sqrt{G \cdot \mathrm{EIRP}/P_L}(c/4\pi f)$, which is the distance from the reader where the tag collects enough power to activate the microchip transmitter. d has been computed for an $\mathrm{EIRP} = 0.5$ W (highest value allowed by European regulations) and chip input power $P_L = 1$ mW [1].

Optimization results, with weight $r_1 = 9.49$, $r_2 = 0.5$, $r_3 = 0.01$, are shown in Fig. 3 for $\mathrm{N} = 1$ antennas and in Fig. 4 for $\mathrm{N} = 2$ antennas. The copper U-MLAs obtained by curves of Fig. 2 are also reported for reference. It can be noted that the optimum usage of the wire current and the space occupation is different and it is strongly related to the wire conductivity as it is visible from the different shapes. Lossless-wire antennas are the shortest ones and exhibit nearly the same gain as a half wavelength dipole, with size reduction factor $\beta = (\max(W_p, H_p)/(\lambda/2))$ of about 23%. Lossy conductor MLAs tend to fill all the available area and their horizontal segments originating transmission line stubs are shorter close to the source in order to minimize the transmission line current, which does not contribute to radiation. In comparison with the U-MLA of the same order, the optimized copper antennas show a gain enhancement of 0.3 dB $(\mathrm{N} = 1)$ and 1 dB $(\mathrm{N} = 2)$ and consequently the reading range has been improved by about 3 cm $(\mathrm{N} = 1)$ and 5 cm $(\mathrm{N} = 2)$, respectively. The total wire length L is similar for NU-MLA of the same order and ranges between 0.6 λ and 0.67 λ. The input impedance is $Z_{in} \simeq 10\ \Omega$ for the copper-wire antenna and it is close to the load impedance of commonly used microchip transmitters [1]. Although not an optimization parameter, the bandwidth has been improved by about 10% in moving from copper U-MLA_1 to the optimized NU-MLA_1 since the latter tends to occupy more space.

To discuss the performances of optimized self-resonant copper MLAs of a *same size*, two new design sets have been produced (Fig. 5) having fixed the available size to that of two U-MLA_1s with $\mathrm{H} = 4$ cm $(\mathrm{W} = 2.8$ cm$)$ and $\mathrm{H} = 5$ cm $(\mathrm{W} = 2.6$ cm$)$, respectively. The following optimization weights in (1) favor gain maximization: $r_1 = 9.8$, $r_2 = 0.01$, $r_3 = 0.19$. A top-loaded dipole ("C" antenna) tuned by



	NU-MLA1	NU-MLA2	Top-Loaded	NU-MLA1	NU-MLA2	Top-Loaded
(W,H)	2.8 , 4.0	2.8 , 4.0	2.8 , 4.0	2.6 , 5.0	2.6 , 5.0	2.6 , 5.0
G (dB)	0.30	0.48	0.14	0.83	1.01	0.76
L/λ	0.60	0.69	0.76	0.59	0.65	0.73
η(%)	67	68	68	76	77	79
Rr (Ω)	5.4	7.4	8.8	8.6	9.8	13.7
Rj (Ω)	2.8	3.2	4.1	2.7	3.5	3.6

Fig. 5. Optimized antennas with the same size (W,H in cm) of two U-MLA_1. A top loaded dipole is also shown for comparison. R_r and R_j are radiation and loss resistances, respectively. The gain of the two U-$\mathrm{MLA}_1\mathrm{s}$ are 0.30 dB $(\mathrm{H} = 4~\mathrm{cm})$ and 0.81 dB $(\mathrm{H} = 5~\mathrm{cm})$.

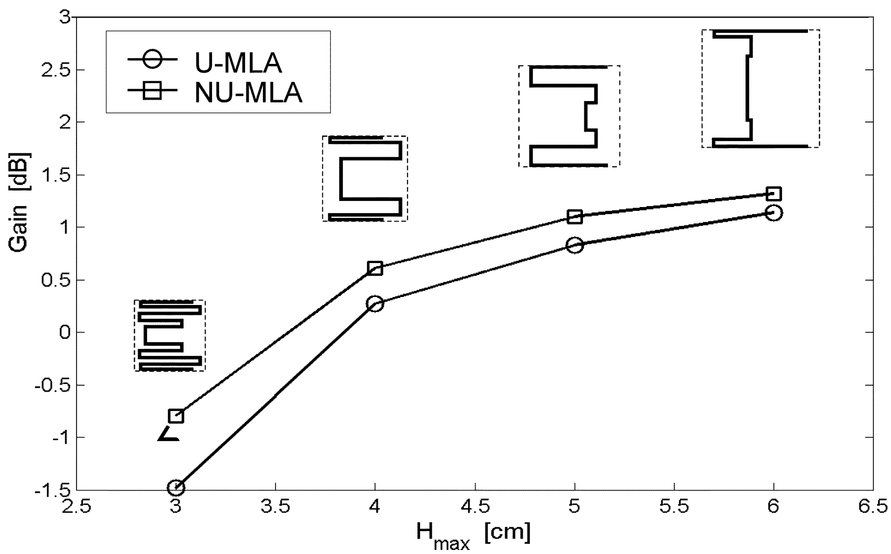


Fig. 6. Copper-wire GA-optimized NU-MLA antennas for different maximum available areas $H_{\max} \times H_{\max}$ (dashed shapes). The gain of the corresponding U-MLA antennas are also reported.

some foldings, which is a simple way to miniaturize a dipole, has been also considered for reference. While no sensible improvement over the U-MLA_1 has been appreciated in optimized NU-MLA_1, better performances have been obtained with NU-MLA_2. It is possible to verify that the antenna loss increases with the wire length while the radiation resistance is higher in those designs with prevalent vertical shape near the voltage source, where the current peaks (e.g. the NU-MLA_2 and the top-loaded dipole). Therefore, having fixed the antenna height, the radiation resistance depends on "how effective" is the current usage in the wire path. The highest radiation resistance is that of the top-loaded dipole whose central vertical segment has the longest length which is permitted in the available space. However, the wire length of this antenna and, hence, the loss resistance are the highest. Accordingly, the gain is lower than that of the U-MLA_1. The best antennas, in the sense of (1), are the NU-$\mathrm{MLA}_2\mathrm{s}$ which show the best tradeoff between wire length minimization and best current utilization. The gain improvement over the two U-MLA_1 has been of about 0.2 dB in both the considered sizes. It is interesting to note that above results partially disagree with what stated in [5], e.g., that the radiation resistances of shaped dipoles of fixed height are similar, independent of antenna geometry and total wire length. Nevertheless, no information about the antenna horizontal size is given in that paper.

Finally, to further investigate on the ability of the GA optimization to enhance MLA gain, some more designs have been performed for different maximum size $(H_{\max} \times H_{\max})$ ranging from $3 \times 3~\mathrm{cm}^2$ to $6 \times 6~\mathrm{cm}^2$. As depicted in Fig. 6, the GA-optimization is as much effective over the uniform MLA as the maximum available area decreases. For sizes smaller that $4 \times 4 \times~\mathrm{cm}^2$ a $\mathrm{N} = 2$ antenna has been considered to obtain self resonance. As the available space increases, the antenna tuning requires shorter horizontal segments, mainly localized at the wire's ends to minimize losses. The MLAs therefore converge to a single-fold top-loaded dipole which, as discussed above, has the best current utilization.

IV. Conclusion

Miniaturized self-resonant meander-line antennas have been designed by GA optimization. It has been numerically experienced that: 1) the optimum usage of the wire current is strongly related to the wire loss strength; 2) for a fixed *maximum* available space, optimized NU-MLAs perform better than same-order U-MLAs (up to 1-dB gain improvement for copper wire); 3) same order MLAs (uniform and optimized) of *same* size exhibit similar performances, while gain enhancement is possible by adding further degrees of freedom, e.g. by higher order NU-MLAs; and 4) in all the considered cases, optimized MLAs perform better than top-loaded dipoles having the same size. This class of antennas may be useful as an extremely small tag for radiofrequency identification applications involving a reading range of about 0.5 m and with a bandwidth of a few megahertz.

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REFERENCES

[1] K. Finkenzeller, *RFID Handbook*. London, U.K.: Wiley, 1999.
[2] T. J. Warnagiris and T. J. Minardo, "Performance of a meandered line as electrically small transmitting antenna," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 1797–1876, Dec. 1998.
[3] G. Marrocco, A. Fonte, and F. Bardati, "Evolutionary design of miniaturized meander-line antennas for RFID applications," in *Proc. IEEE AP-S Int. Symp.*, vol. 2, San Antonio, TX, 2002, pp. 362–365.
[4] G. J. Burke and A. J. Poggio, "Numerical Electromagnetic Code (NEC) Method of Moments," Naval Ocean Syst. Ctr., CA, Tech. Doc. 116, pt. I and II, 1980.
[5] S. Best, "On the resonant properties of the Koch fractal and other wire monopole antennas," *IEEE Trans. Antennas Wireless Propagat. Lett.*, vol. 1, pp. 74–76, 2002.
[6] D. S. Weile and E. Michielsen, "Genetic algorithm optimization applied to electromagnetics: a review," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 343–353, Mar. 1997.
[7] Inks for RFID Antennae. Parmod VLT Tech. Rep. [Online]. Available: www.parelecusa.com/parelec3/product/images/RFID.pfd