Design of a Broadband HF Antenna for Multimode Naval Communications

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***Abstract*—This paper describes a multifunction HF-loaded antenna for broadband naval communications based on both groundwave and near vertical incidence skywaves. The antenna, denoted as *bifolded monopole*, is designed according to a new loading strategy which avoids the use of complicated external networks. Numerical simulations and measurements on a scaled prototype have shown that interesting capabilities are obtained by using just four or five loading circuits.**

***Index Terms*—Broadband antennas, HF antennas, loaded antennas, naval communications, software radio.**

I. Introduction

RECENT advances in software radio technology [1] are originating a renewed interest in HF multichannel communication systems. The antenna features are a key issue. Beside the broadband requirements, antennas should be compact enough to be placed within a ship scenario and should permit communication at both low- (groundwave) and high-elevation [near vertical incidence skywave (NVIS)] angles. In actual shipborne systems, these requirements are commonly split among multiple antennas, such as whip-types for communications at the horizon and beyond line of sight (BLOS), and fan-types antennas or loops for NVIS links (2–7 MHz) [2], [3]. HF antenna systems, therefore, require large space and complicated distributed feeding networks. Compact broadband whip and fan antennas have been designed by loading simple wire shapes with lumped or distributed traps (stubs [4], parallel resistor–inductor–capacitor (*RLC*) circuits [5], [6], dielectric and magnetic beads [7]) and using a proper matching network.

This paper proposes a new wire antenna geometry, of size suitable for naval installation, having multimode capabilities in the sense that it combines the possibility to simultaneously provide groundwave and NVIS links with broadband features. Such a geometry is obtained from a folded monopole by adding further current paths and introducing some lumped impedances with the twofold purpose of broadband radiation pattern synthesis and antenna matching. Unlike conventional *RLC*trap loading, the proposed strategy involves the placing of isolated resistors, parallel, and series inductor–capacitor (*LC*) circuits, by whose combination more complex topologies can be obtained. This strategy will permit to avoid the need of a matching network which instead is here practically distributed all over the antenna.

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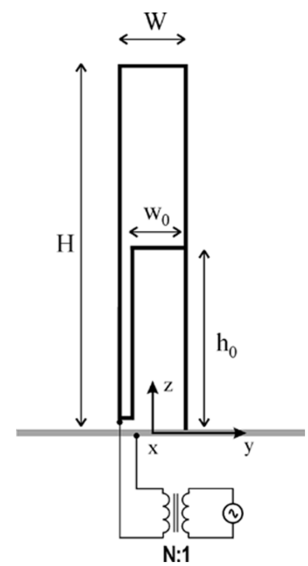

Fig. 1. Geometry of the *bifolded monopole* over an infinite ground plane. The impedance transformer ratio N will be optimized together with antenna loading. Antenna size: $H = 12$ m, $W = 2$ m, $h_0 = H/2$, $w_0 = 1.6$ m.

II. The Unloaded Bifolded Monopole

To achieve multimode functionalities, the antenna geometry needs to include the shape of a monopole and that of a half loop for NVIS radiation. Accordingly, the proposed geometry, hereafter denoted as *bifolded monopole*, is shown in Fig. 1. This is obtained as modification of a simple folded monopole, already considered as groundwave HF antenna in [5], where the addition of a nested wire improves the space filling of the antenna and permits to create more complex meander paths useful for antenna miniaturization [8]. The expected benefit will be a bandwidth improvement or, from a different point of view, a simpler antenna broadbanding task.

Fig. 2 shows the input impedance of the unloaded bifolded monopole in comparison with a folded monopole having same sizes, as computed by the method of moments [9], under the assumption that the antennas are placed onto a perfect ground plane. It can be observed that the folded monopole exhibits a short-circuit condition around 12 MHz ($R_{\text{in}} \simeq 4\ \Omega$) corresponding to the loop antiresonance ($2H + W \simeq \lambda$). Around this frequency it will be rather difficult to match the antenna, even with trap loading, unless a sensible lowering of the efficiency. On the contrary, the bifolded geometry does not show a so huge short-circuit around that frequency and the minimum

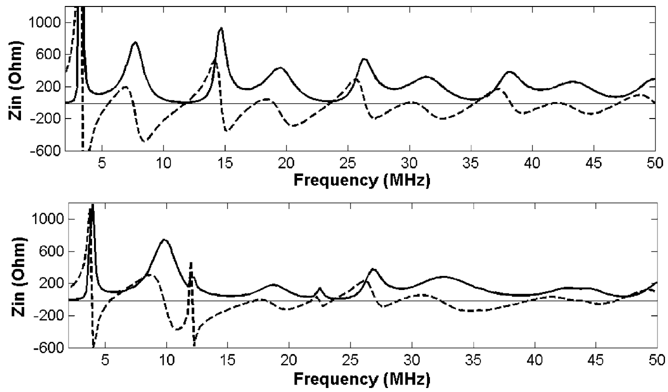

Fig. 2. Input impedance in the range 2–50 MHz of the unloaded folded monopole (up) and of the new bifolded monopole (down) of size in Fig. 1. Solid and dashed lines respectively refer to real and imaginary part of the input impedance.

value of its input resistance occurs around 24 MHz ($R_{\rm in} \simeq 10\,\Omega$). Moreover, the impedance curves are less oscillating than that of the folded monopole and it is therefore expected that an easier matching will be possible for the new antenna.

III. Broadbanding Strategy

To exploit broadband and multimode features, the antenna in Fig. 1 is loaded by means of passive lumped electric devices which will enforce the most suitable current path at each frequency. Reasonable requirements for the loaded system are $\rm VSWR < 3$ within the whole HF band, antenna efficiency larger than 50%, gain higher than -20 dB at NVIS, higher than -10 dB along the horizon for $2\ {\rm MHz} \leq f \leq 5\ {\rm MHz}$, and higher than $2{\rm dB}$ above 5 MHz. The allowed range of the electric components needs to be properly defined at the purpose to obtain feasible values. In particular, large values of inductance or transformation ratio involve large coils which can get self-resonating [10] in the upper part of HF range. Concerning the resistor limitations, large resistances could require cooling systems to be distributed along the wires for high power dissipation at low frequencies where the antenna efficiency is small. The parameters' ranges which will be considered throughout this paper are: $50\ {\rm nH} \leq L \leq 3\ \mu{\rm H}$, $5\ {\rm pF} \leq C \leq 1\ {\rm nF}$, $R \leq 100\ \Omega$. Within these limits, the authors verified that the above gain and matching requirements cannot be achieved, at a same time, by using conventional *RLC* traps and typical lossless networks [5], [6] plus a frequency independent attenuator and an impedance transformer. Therefore, a different strategy has been here adopted. The matching network only retains an impedance transformer while loading components are distributed along the antenna according to multiple topologies. The basic circuits are the isolated resistor and both the series and the parallel *LC*s, which can respectively act as short- and open-circuit at their natural frequency. By also introducing individual resistors it is possible to synthesize a proper frequency dependent attenuator all over the antenna and, since more loading impedances are allowed to share, as a series connection, a same position along the wire, more electrical topologies can be attained.

The optimization of antenna loads (number, topology, position, and values) and of the impedance transformer is achieved with respect to the minimization of the following penalty function depending on matching and on gain requirements as shown in (1) at the bottom of the page.

Here, N_f is the number of frequency samples in the HF band (tagged by index n), $F_{\rm VSWR}^{(n)}$ is a threshold function controlling the matching ($\rm VSWR < 3$), $F_{\eta}^{(n)}$ controls the system efficiency, $F_{Gh}^{(n)}$ the system gain value and uniformity along the horizon ($\theta = 90^\circ$), while $F_{\rm NVIS}^{(n)}$ accounts for the radiation at NVIS angles ($\theta = 20^\circ$). Finally, $F_{\rm traps}$ tries to minimize the number of loading impedances. Parameters $w_j^{(n)}$ are frequency-dependent in order to selectively weigh the gain and matching requirements in different parts of the frequency range. For instance, at lower frequencies (2–4 MHz) the weight of matching penalty ($F_{\rm VSWR}^{(n)}$) is more emphasized than those affecting the gain. The genetic algorithm (GA) [11], which is a commonly used tool to design loaded antennas, is applied for solving the optimization problem together with the method of moments for antenna analysis. The evaluation of the features of each population member (e.g., a loaded antenna) is achieved by the fast method described in [6] which requires the inversion of small matrices, of size depending only on the loads' number.

IV. Results

The loading of the bifolded monopole has been optimized having set to 10 the maximum number of loads. Conductors are assumed to be aluminum pipes with 8.5-cm diameter. At purpose of comparison, the folded monopole of same size also has been optimized according to the proposed strategy.

Fig. 3 shows the loading topology of the bifolded monopole as found by GA. Four circuits have been required while seven circuits have been necessary for the folded monopole.

Although both the folded and the bifolded antennas are well matched in a band which is even larger than the required HF region, the proposed antenna shows superior performances, as concerns the gain and the efficiency (Fig. 4). The ϕ-averaged gain of the bifolded is higher and more uniform up to 40 MHz whereas the folded monopole gain drops under 2 dB in many parts of the band. The efficiency of the new antenna is higher than in the case of the conventional folded monopole in particular for $7\,{\rm MHz} \leq f \leq 15\,{\rm MHz}$ e.g., around the sharp short-circuit effect which appears in the input impedance of the unloaded structure as discussed in the previous paragraph. In this case, the

$$F = \frac{1}{N_f}\sum_{n=1}^{N_f}[w_1^{(n)}F_{\rm VSWR}^{(n)} + w_2^{(n)}F_{\eta}^{(n)} + w_3^{(n)}F_{Gh}^{(n)} + w_4^{(n)}F_{\rm NVIS}^{(n)}] + w_6F_{\rm traps}. \tag{1}$$

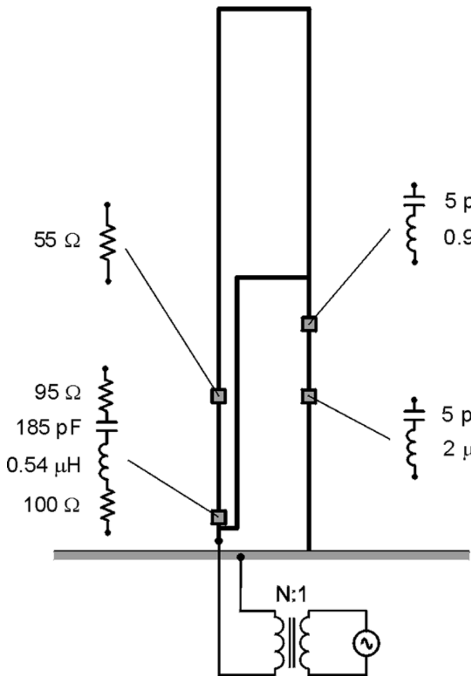

Fig. 3. Optimized loads for the bifolded monopole. The transformation step-up ratio has been set to 3.4.

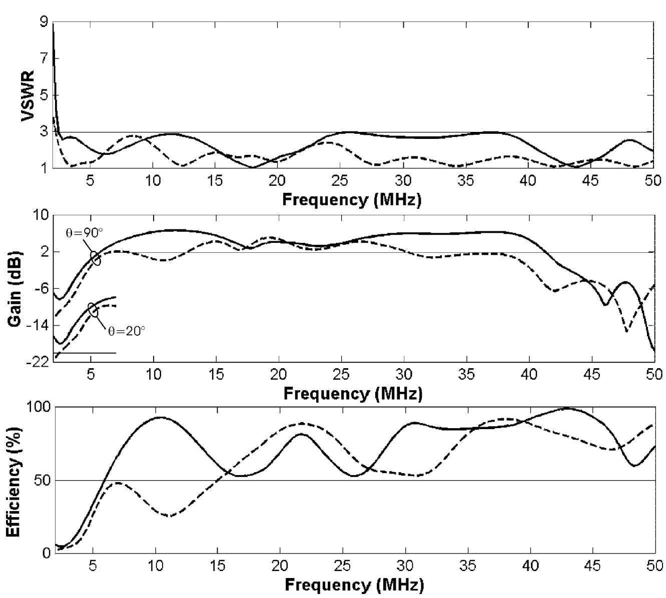

Fig. 4. ϕ-averaged gain at the horizon and at $\theta = 20°$, and system efficiency after loading optimization in the range 2–50 MHz. Solid lines tag the bifolded monopole loaded with four circuits, while dashed curves are for the reference folded monopole having the same size of the proposed antenna, and loaded with seven circuits.

low efficiency of the folded monopole is the price to pay to have the antenna matched.

By inspection of the current patterns of the loaded bifolded monopole (Fig. 5), it is evident the combination of the different current paths, loop and monopole modes in particular, which were allowed by the proposed geometry. At 2.5 MHz the equivalent electric monopole current is the difference between currents along segments a and b, while the magnetic dipole results from

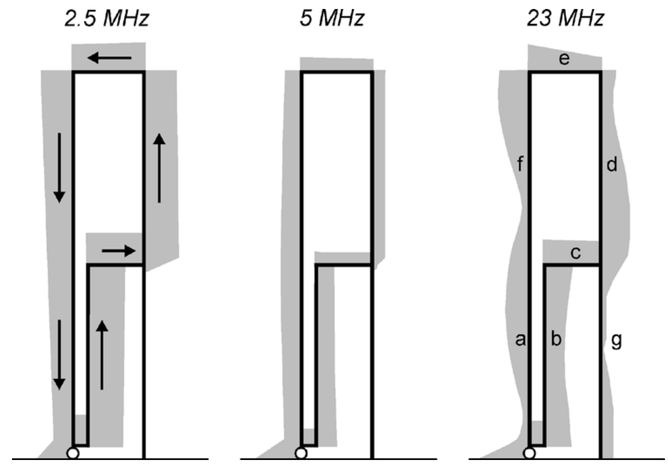

Fig. 5. Current patterns (amplitude) at some frequencies. Arrows indicate the current direction.

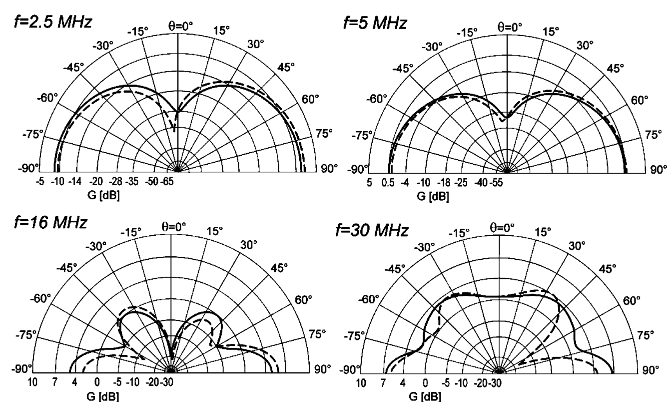

Fig. 6. Radiation patterns at some frequencies. Solid line: $\phi = 0°$ cut; dashed line $\phi = 90°$ cut.

the current path c, d, e, f. The lower vertical wire, g, connected to ground is isolated by the two high-impedance series *LC* loads of Fig. 3 (which resonate at $f = 50.3$ MHz and $f = 74.6$ MHz, respectively) and, therefore, it does not much contribute to radiation at low frequencies while it is active at higher frequencies. Radiation patterns in Fig. 6 indicate NVIS gain performances and an almost omnidirectional radiation along the horizon.

A different optimized topology is presented in Fig. 7 where the loading resistors are constrained, within the GA optimization, to be placed only close to the ground plane: this condition could be useful whenever the antenna has to handle high power and cooling equipment need to be considered. In this case, the system requirements previously introduced, are matched by using only three *LC* circuits and two close resistors which can be integrated into a single circuit. For this configuration a 1:50 scaled prototype (Fig. 8) on a finite 2 $m \times 1$ m ground plane has been developed and measured within the band 100 MHz $\div$ 2 GHz. To simplify the component assembly, it has been considered $w_0 = 2/5W$.

The VSWR in Fig. 9 is in good agreement with the numerical model up to 1 GHz corresponding to 20 MHz for the 1:1 antenna. As the frequency increases, the inductors move from their nominal values, the circuits' sizes start to become comparable with the wavelength, whereas in the simulations the loads

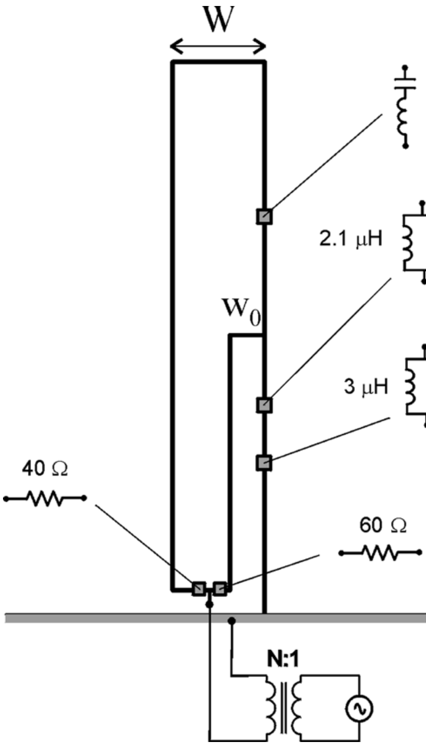

Fig. 7. Loading topology of the bifolded monopole when resistors are contrained close to the ground plane. The trasformation step-up ratio has been set to 4.

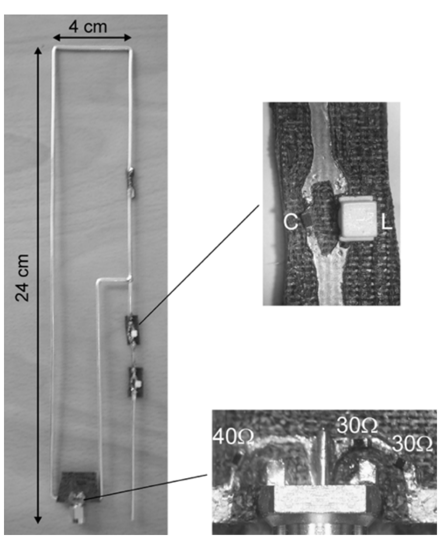

Fig. 8. Scaled model (1:50) of the bifolded antenna in Fig. 7. The conductor is a 2-mm diameter copper wire. Loading electric devices are sustained by a dielectric substrate. On the right, some details about the loading circuit realization: the 60-Ω resistor has been obtained as series connection of two 30 Ω ones.

are supposed of negligible size, and therefore, experimental data agree less well with simulations.

V. Conclusion

The proposed antenna is simple to build and could be derived from a conventional twin whip configuration augmented

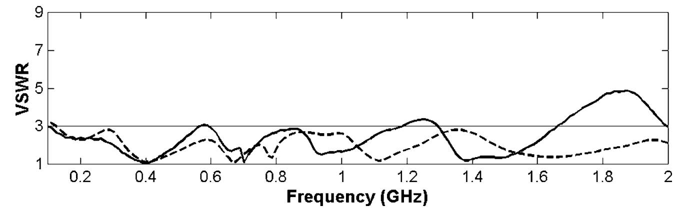

Fig. 9. VSWR of a bifolded monopole with resistors constrained close to the ground plane (Fig. 7). Simulated data (dashed line) are compared with measurements (solid line) on the 1:50 scaled prototype in Fig. 8.

with some wires. Comfortable maintenance is possible since the loading circuits are placed at a close distance from the ground. In a real installation, the presence of the ship could potentially modify the antenna features. It has been verified that the ship-to-sea discontinuity does not sensibly affect the antenna gain, VSWR, and efficiency, provided that the sea is still modeled as a perfect ground plane. In the case where the sea is modeled by a finite conductivity, the gain close to the horizon, as expected, is sharply reduced within a small angle, while the matching and the efficiency are practically unchanged. Finally, the cohabitation of the proposed antenna with other naval structures depends on the particular scenario and it is expected to share the same coupling features than any whiplike antenna.

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