Frequency-Scanned Focused Leaky-Wave Antennas for Direction-of-Arrival Detection in Proximity BLE Sensing Applications

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***Abstract*— The synthesis of monopulse functions in the Fresnel region, using near-field focused leaky-wave antennas (LWA), is presented in this work. The focusing technique, combined with the frequency-scanning behavior of LWAs, allows for obtaining well-defined radiation patterns in the vicinity of the antenna, which properly overlap to obtain the scanning monopulse functions. This is not possible with conventional far-field focused antennas, in which the radiation pattern is very distorted in the near-field region. As a proof of concept, examples using the three advertising channels provided by the Bluetooth Low Energy (BLE) protocol are shown. These channels (#37, #38 and #39) are placed at 2.402, 2.426 and 2.48 GHz, respectively. The near-field monopulse synthesis is interesting for Direction-of-Arrival (DoA) detection in proximity sensing applications.**

***Index Terms*—Bluetooth Low Energy, Direction-of-Arrival, leaky-wave antennas, near-field focusing, proximity detection.**

I. Introduction

In the frame of Internet of Tings (IoT), proximity sensing and micro-localization of mobile devices using deployed wireless networks, has become a key enabling technology towards Smart Areas. Direction-of-Arrival (DoA) estimation allows localization of a mobile device with respect to a reference. One approach for the DoA estimation is the monopulse technique using radio beacons in the 2.4 GHz ISM band, as proposed in [1]–[3]. In these scenarios, it is very common that the mobile device is located in the near-field radiative zone (Fresnel region) of the monopulse antenna. As recently demonstrated in [4], once entering the Fresnel zone it is necessary to correct the monopulse functions for a good DoA estimation. In this paper we extend the results of [4] for larger monopulse antennas which are needed for higher angular resolution, and which suffer from greater near-field distortions. Moreover, here we analyze the near-field effects in a monopulse leaky-wave antenna (LWA) [5], [6], which combine high angular resolution with a wide Field of View by frequency-scanning several directive beams. As it is shown in this paper, the directive beams are strongly distorted in the near-field region, and this implies that monopulse functions cannot be used for proximity DoA.

To mitigate this unwanted effect, we propose the use of focused LWAs that confine the power in one spot in the near-field region. This way, a well-defined directive pattern can be formed in the Fresnel region, allowing for the use of monopulse functions for DoA detection when the device is in the surroundings of the antenna. Thus, higher resolution in the angular estimation of the position of devices located in close proximity to the reader can be achieved. As a practical example, the frequency-scanning monopulse LWA is tuned to the three advertising channels of the Bluetooth Low Energy (BLE) protocol (namely #37, #38 and #39, at 2.402, 2.426 and 2.48 GHz). These channels are sequentially swept by BLE beacons for location purposes [6], [7].

The rest of the paper is organized as follows: in Section II, an overview of the use of LWAs for synthesis of frequency-scanned monopulse is presented. Then, some results on the performance of the monopulse system in the near-field region are shown in Section III. Section IV is dedicated to present a near-field focused LWA to palliate the degradation of the monopulse functions near the antenna, showing some results and discussing its limits. Finally, some conclusions are summarized in Section V.

II. Leaky-Wave Antenna for Frequency-Scanned Monopulse Synthesis

The synthesis of frequency-scanned monopulse functions for DoA estimation was proposed in [5]. This technique is based on bi-directional LWAs, which change the direction of the radiation pattern depending on the frequency of the signal. By feeding a LWA through its two opposite ports (called P1 and P2 in the rest of the manuscript) and by using different frequencies, several directive beams can be created. Each of the beams points at a different direction and all of them properly overlap to create monopulse functions. In this work we follow the same approach, using the frequencies of the three advertising channels from the BLE protocol, as indicated in the introduction section. In this way, six beams can be synthesized, three from each port of the antenna. For high resolution of the monopulse functions and thus, of the DoA estimation, very narrow beams must be used. Thanks to the use of the frequency-scanning technique [5], a relatively wide Field of View (FoV) can be covered using six narrow beams. This is illustrated in Fig. 1a, showing that six directive beams are scanned to cover an approximate FoV [-25º, 25º], and using the three BLE advertising channels. To obtain an optimum monopulse function, the beams should overlap at their half-power points, this is, at -3dB with

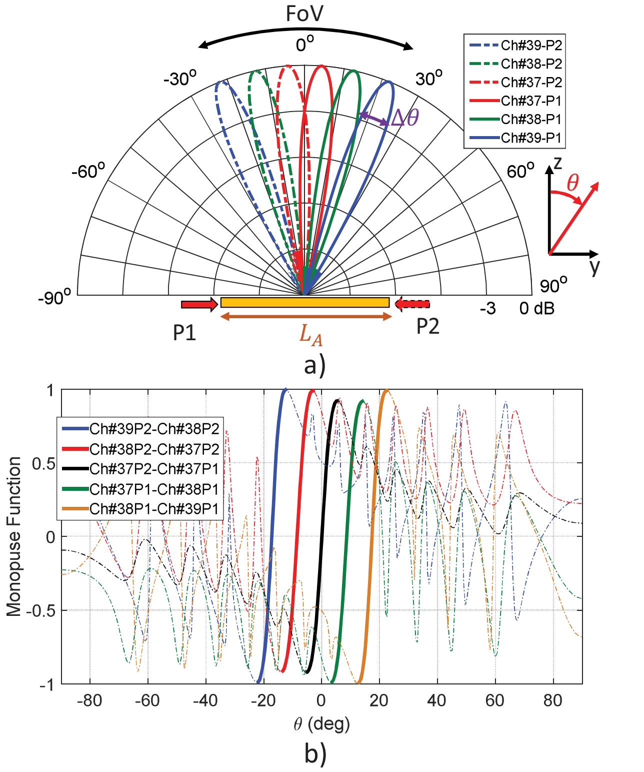

Fig. 1. a) Far-field frequency-scanned beams for high-resolution monopulse FFF LWA. b) Synthesized monopulse functions.

respect to their maximum value. For this, the half-power beamwidth has to be $\Delta\theta$ =8.5º. In LWAs, the beamwidth is directly related to the antenna length, L_A, by the next approximation [8]:

$$\Delta\theta \approx \frac{1}{\frac{L_A}{\lambda_0}\cos\theta_R} \quad (1)$$

where λ_0 is the free-space wavelength and θ_R is the radiation angle. This implies that, if a narrow beam wants to be synthesized, longer antennas must be used. In the case of Fig. 1, the antenna length is L_A=76 cm (≈6λ_0 at 2.45 GHz). More details on the design of the antennas will be given in the oral presentation. Combining contiguous beams in pairs, five scanned monopulse functions can be synthesized with high resolution (related with the slope of the curves), and covering the aforementioned FoV of 50º, as depicted in Fig. 1b. The signal processing technique presented in [5] can be applied for accurate estimation of the DoA of a BLE device, using the associated multi-frequency beacon signal.

III. Near-Field Region Effects

The patterns shown in Fig. 1, using an antenna with length L_A=76 cm, represent the power distribution of the radiation in the far-field region, this is, at high distances from the LWA. For this, a Far-Field Focused LWA (FFF LWA) is needed, meaning that the antenna must be designed with the restrictions of the beams in the far-field region.

As explained in Section I, for some applications it is necessary to detect the DoA of an object at short distances from the sensor. For this, an evaluation of the performance of this LWA in the near-field region must be carried to see the feasibility of monopulse synthesis. The change in the radiation pattern as we get close to a shorter monopulse antenna was reported in [4]. There it was shown that depending on the distance between the sensor and the object, different monopulse functions must be used to correct for the near-field effects. As it was done in that work, the fields in the surroundings of the antenna must be evaluated, so in Fig. 2, the near-field power distribution in the vicinity of the LWA (plotted with a yellow rectangle) is represented for the three BLE frequencies and using P1. As it is well-known [9], the directive scanned beam is only defined at a distance sufficiently far from the aperture, as it can be clearly seen in Fig. 2.

To better understand this effect in the near-field radiation patterns, an angular cut at a distance of d=50 cm from the LWA is illustrated in Fig. 3. In contrast to the results shown in Fig. 1a, it is clear that the beams are no longer well defined when we get close to the antenna aperture, so it is impossible to obtain proper monopulse functions to estimate the DoA by using the FFF LWA. This is due to the big size of the antenna in our case, chosen to achieve high angular resolution. Instead, as will be demonstrated in Section IV, a Near-Field Focused LWA (NFF LWA) is key for the synthesis of proper monopulse functions with high resolution for proximity applications.

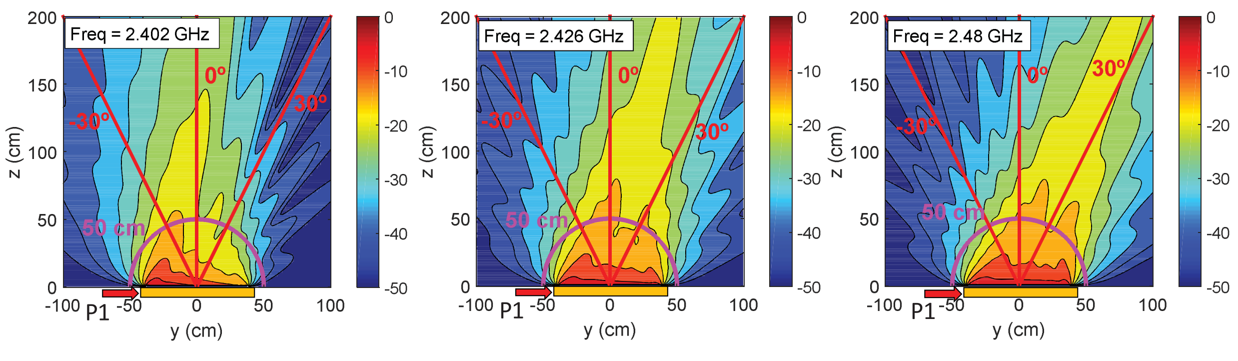

Fig. 2. Near-field region power distribution of the FFF LWA for a) BLE channel #37 b) BLE channel #38 c) BLE channel #39.

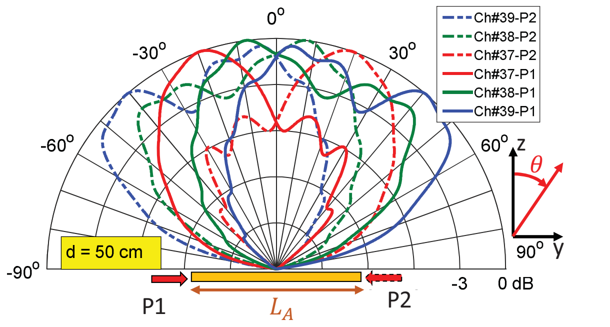

Fig. 3. Angular power distribution of the FFF LWA at a near-filed distance of d=50 cm for the three BLE channels.

IV. Near-Field Focused Design

Focusing techniques are well known from the point of view of antenna design [10]. The synthesis of a focus was reported in [11], [12], but there was not reconfigurability of the position of the focal point. LWAs offer the capacity to easily synthesize a focus by tapering the structure. Besides, the focus of NFF LWAs can be scanned by changing the feeding frequency, as demonstrated in [13]–[15]. Another way to control the focal position with LWAs is by using electronic scanning [16], but this requires a complex control network. Moreover, the combination of this two techniques was proposed in [17] for 2-D scanning of a focus.

With the aim of creating defined directive beams in the near-field region, a NFF LWA with a focal point at d=50 cm from the antenna and similar aperture length L_A=76 cm than the previous FFF LWA is designed using the synthesis technique of [13]. The power distribution in the vicinity of the antenna is plotted in Fig. 4. Now, it can be clearly seen that a well-defined directive beam is scanned at this close distance of 50 cm for the three design BLE frequencies. The angular cut represented at d=50 cm (purple line) is plotted in Fig. 5a. Six well-defined directive beams are synthesized at this short distance, covering a wide FoV of 50º, as it was done for a large distance in the FFF LWA design in Fig. 1a. Similarly, the six directive beams can be compared to obtain the corresponding five monopulse functions, which are represented in Fig. 5b. The beams at channels #37 and #38 in Fig.5a overlap more than in Fig.3, since the scanning of a near-field beam is not necessarily the same as the one of a far-field beam. This affects the slope of the near-field monopulse function when comparing channels #37 and #38. Despite this, the monopulse technique can be used to properly estimate the DoA with high resolution at a near-field distance of d=50 cm (well in the Fresnel zone of a large aperture L_A=76 cm), which cannot be obtained with a FFF design.

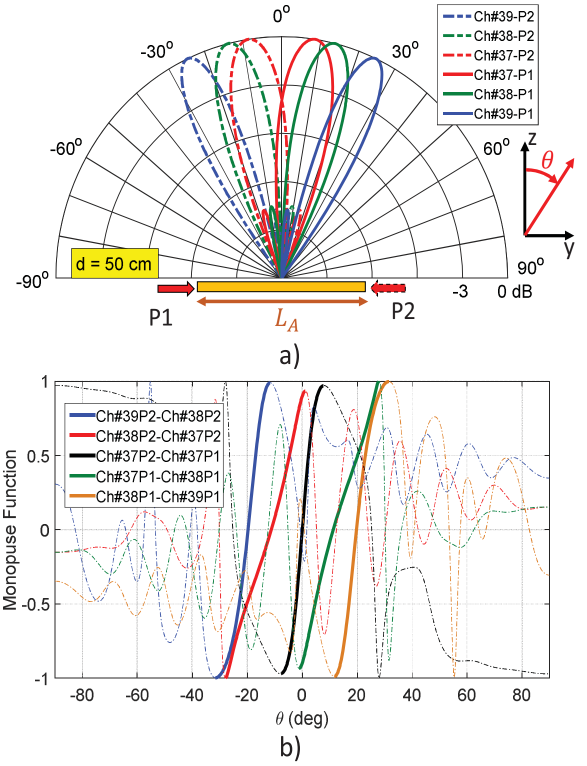

Fig. 5. a) Angular power distribution of the NFF LWA at a near-filed distance of d=50 cm for the three BLE channels. b) Synthesized monopulse functions at 50 cm with this NFF LWA.

Lastly, it is important to evaluate the performance of the NFF LWA design in the far-field region. For this, the frequency-scanned far-field patterns of the NFF LWA are depicted in Fig. 6. As it can be seen, due to the field divergence far from the focal distance of d=50 cm, the patterns are defocused in the far field zone. As a result, broad tilted beams with high secondary lobes are observed in Fig. 6, and they are not suitable anymore for directive monopulse

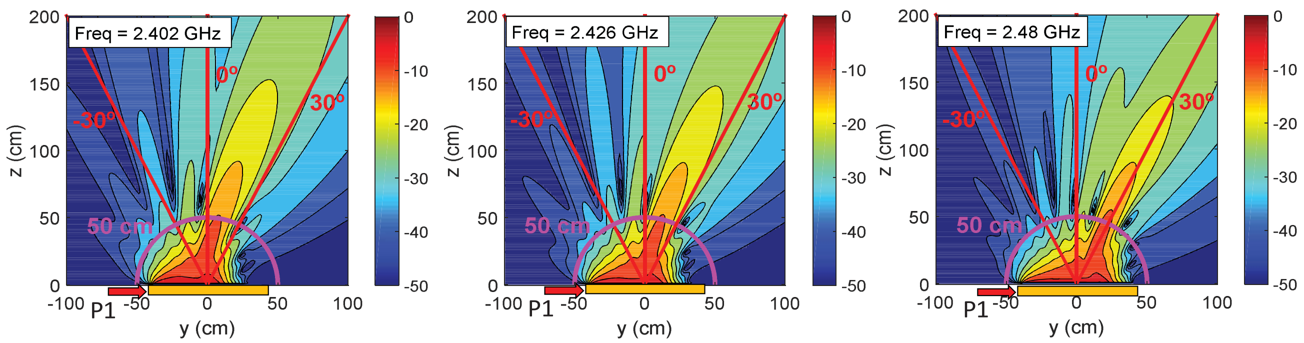

Fig. 4. Near-field region power distribution of the NFF LWA for a) BLE channel #37 b) BLE channel #38 c) BLE channel #39.

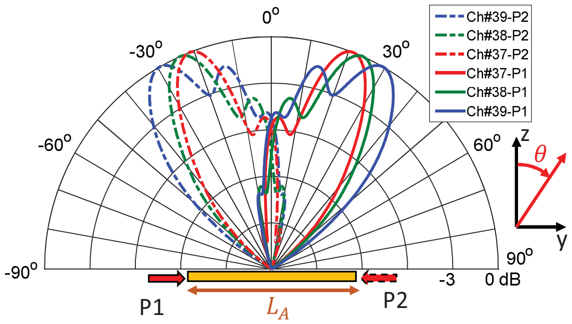

Fig. 6. Far-field frequency-scanned beams of the NFF LWA for the three BLE channels.

pattern synthesis. This effect is expected, since near-field focusing techniques are also used to synthesize broad beams in the far field, as explained in detail in [18]. For this reason, the NFF LWA is a good candidate for proximity applications, but cannot be used for far-field applications. Reciprocally, FFF LWAs are not valid for near-field applications. This trade-off is more significant for longer antennas. Thus, large antennas with potential high directivity must be properly focused at the requested focal distance, in order to avoid loss of angular accuracy due to unwanted broaden of the beams.

V. Conclusion

The unwanted effects when working in the Fresnel region of a far-field focused, frequency-scanning, monopulse leaky-wave antenna, have been evaluated for the first time. It has been shown that the directive scanning performance is strongly degraded in the proximity of the antenna aperture. To overcome this problem, the use of a frequency-scanning leaky-wave antenna focused in the near-field radiative zone, has been proposed and validated with theoretical results. The design demonstrates well-defined scanned directive beams in the vicinity of the antenna. This allows for high-resolution direction-of-arrival estimation in a wide angular area for proximity sensing applications.

The scanning antennas have been designed to operate with the three advertising channels of BLE beacons in the 2.4 GHz ISM band, to demonstrate its applicability for practical wireless location systems. A wide field-of-view of 50º at a short distance of d=50 cm (well in the Fresnel zone of a large aperture L_A=76 cm), has been scanned with six directive beams. This directive angular performance for proximity-location applications cannot be obtained with a far-field focused design. Moreover, the focal distance must be adequately chosen to avoid undesired divergence of the beams, which reduces the angular detection accuracy.

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