Wearable Magnetoinductive Waveguide WBANs: Tolerance to Loop Failures

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***Abstract*—We recently reported a new class of wearable wireless body area networks (WBANs) that are based on magnetoinductive waveguides (MIWs) to offer extremely low loss as compared to the state-of-the-art. These WBANs consist of a series of resonant loops placed in either axial or planar configuration upon the human body. Contrary to other continuous connecting structures for WBANs that fail in case of any break, these MIW WBANs are tolerant to any break/loop failure. In this paper, we provide quantitative results to demonstrate the above and we assess the effect of loop failures on performance (loss, bandwidth, and cut-off frequencies). Two loop densities (11- and 15-loop for a distance of 41 cm between transmitter and receiver) are evaluated for both axial and planar designs. We show that axial designs are more tolerant than planar designs, with both designs remaining operational in the event of loop failure.**

***Keywords*—Loop failure; magnetoinductive waveguides; tolerance; wearable; wireless body area networks.**

I. INTRODUCTION

We recently reported a new class of wireless body area networks (WBANs) that are based on magnetoinductive waveguides (MIWs) placed in either axial [1] or planar configuration upon the human body [2]. These WBANs are extremely low loss, among other advantages, as compared to the state-of-the-art [1], [2]. Per Fig. 1, the design utilizes propagating magnetoinductive waves (MI waves) via a series of resonant loops to enable communication [1], [2].

As summarized in [2], recently reported works that aim to reduce loss for WBANs rely on continuous connecting structures and either NFC or electromagnetic waves as means of communication. However, such structures are prone to complete failure shall a break occur at any point (e.g. wear/tear at the joint). By contrast, MIW WBANs provide a continuous connection via a discrete design [see Fig. 1]; thus, they continue to function even in the case of break/failure (with some performance degradation instead of complete failure). In our previous studies, we only discussed this aspect qualitatively. Here, it is the first time that we provide quantitative results for both axial- and planar-MIW WBANs, alongside a comparison between the two.

II. SIMULATION SET-UP

The full-wave frequency domain solver of CST Microwave Studio [3] is used for simulations. To emulate the human limb, we use a cylinder (radius = 3.9 cm, length = 50 cm) with 2/3 muscle representing the average tissue properties [4]. Per Fig. 1(a), the axial-MIW WBAN [1] is implemented using N circular resonant loops wrapped around the limb with a gap of g_a between them. Per Fig. 1(b), the planar-MIW WBAN [2] is implemented using N rectangular conformal resonant planar loops with length (l), width (w) and a gap (g_p) between them. For both axial and planar designs, the first loop acts as a transmitter (Tx) and the last (N^{th}) loop as a receiver (Rx), such that the distance between the two is d_{TR} [see Fig.1]. In all cases, a lumped capacitance (C) is added to make the loops resonant [1], [2]. Our study also includes two different loop densities (number of loops per unit distance): N=11 and 15 for a fixed d_{TR}=41 cm. Other design parameters are selected such that an appropriate comparison can be made between the axial and planar design. Specifically, for the axial design, the loop radius is fixed at 4 cm, C = 49 pF, and g_a = 4.1 and 2.93 cm for the 11- and 15-loop designs, respectively. For the planar design [see Fig. 1(b)], g_p = 0.25 cm, C = 57 pF, and (l,w) are made equal to (3.5 cm, 9.1 cm) and (2.5 cm, 10.1 cm) for the 11- and 15-loop designs, respectively. We note that the loop circumference is the same in all cases, leading to similar operating frequency bands for fair comparison. Performance metrics include: (a) minimum loss in the passband, (b) bandwidth, and (c) cut-off frequencies (lower (f_l), and upper (f_u)). The effect of loop failure (n^{th} loop in Fig. 1) is studied by removing the corresponding loop from the set-up.

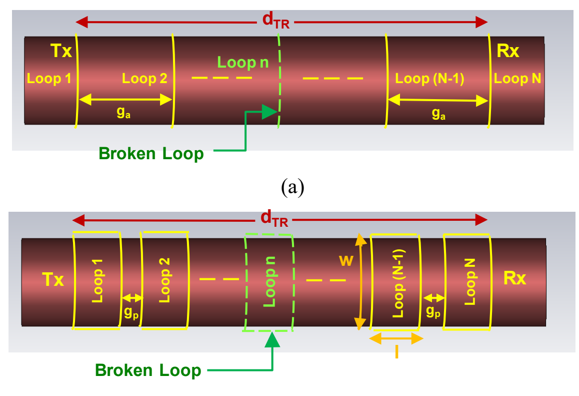
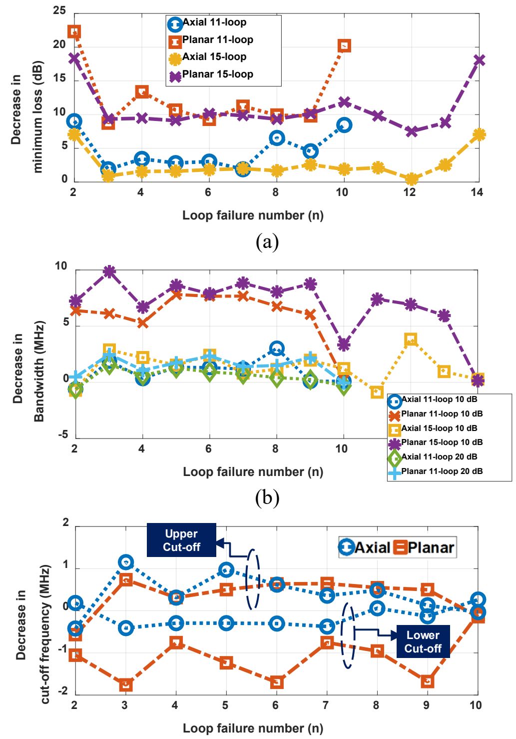


Fig. 1. (a) Axial (wrapped around), and (b) planar (conformal) magnetoinductive waveguide (MIW) WBANs with loop break/failure.



(a)

(b)

(c)

Fig. 2. Results for decrease in (a) minimum loss, (b) bandwidth, and (c) cut-off frequencies when a loop breaks. Results are shown in respect to the location of loop failure for both axial and planar designs.

III. Results

Designs without any loop failure are considered first to serve as reference. These 11-/15-loop axial and 11-/15-loop planar designs exhibit minimum loss of 16.7, 11.79, 9.5, and 11.03 dB, as well as 10 dB absolute bandwidth of 5.39, 7.65, 9.11, and 10.04 MHz, respectively. The 11-loop axial and planar designs exhibit 20 dB absolute bandwidth of 6.73 and 10.52 MHz, respectively, with corresponding cut-off frequencies of (f_u=46.06 MHz, f_l=39.33 MHz), and (f_u=48.85 MHz, f_l=38.33 MHz). In the subsequent analysis, all performance metrics for loop failures are subtracted from the equivalent reference design and, hence, the resulting value provides a net decrease. Loop failure may occur at any point between the Tx and Rx; thus, n varies from 2 to 10 for the 11-loop and from 2 to 14 for the 15-loop designs, at a step size of 1 [see Fig. 1].

Results for decrease in minimum loss and 10 dB absolute bandwidth are depicted in Fig. 2(a) and (b), respectively. As expected, all designs continue to operate but with some degradation in performance. Minimum loss is affected the most when loop failure happens closest to Tx/Rx. An overall improvement is observed with increasing loop density. Although the reference planar design performs better than the reference axial design for the same loop density (especially for lower density) [2], the axial design is significantly more tolerant to loop failure vs. the planar design [see Fig. 2(a)]. For example, for the 15-loop designs (barring the 2nd and 14th loop failure), decrease in loss varies between 7.52 to 11.83 dB for the planar design, and between 0.45 to 2.52 dB for the axial design. For the 10 dB bandwidth, the axial design again performs significantly better vs. the planar design [see Fig. 2(b)]. The above is due to significantly large reflections in the planar design leading to large ripples; as such, the complete passband cannot be captured within the 10 dB bandwidth [1], [2]. Therefore, the 20 dB bandwidth is considered for the 11-loop design and is also included in Fig. 2(b). Results demonstrate that bandwidth decrease is insignificant for both planar and axial designs, including loop failure close to the Tx/Rx, thereby offering quite stable performance. Note that negative numbers for decrease in bandwidth represent an increase in bandwidth and, hence, improvement in performance. Although small, the axial design still shows better tolerance in terms of bandwidth. For example, for the 11-loop design, decrease in the 20 dB bandwidth varies between -0.05 to 2.49 MHz and between -0.6 to 1.56 MHz for planar and axial designs, respectively. In addition, the axial design performs significantly better in terms of reflection/ripples as is evident from the 10 dB bandwidth plots in Fig. 2(b). Finally, Fig. 2(c) plots the decrease in upper and lower cut-off frequencies for the 11-loop axial and planar designs. Here, a simultaneous negative number for decrease in lower cut-off and a positive number for decrease in upper cut-off demonstrate shrinking in the passband and vice versa. For the axial and planar designs, the lower cut-off decrease varies between -0.41 to 0.26 MHz, and -1.75 to -0.08 MHz, respectively. The upper cut-off decrease varies between -0.04 to 1.15 MHz, and -0.57 to 0.73 MHz, respectively.

IV. Conclusion

We demonstrated that both axial- and planar- MIW WBANs continue to operate despite a loop failure. Nevertheless, loop failure leads to reduction in minimum loss, change (reduction or improvement in a few cases) in bandwidth, and change (shrinking or expansion) in the operating band. Loss was found to be affected the most when loop failure happens close to the transmitter/receiver, with much more stable performance for other loop failures (variation of 7.52 to 11.83 dB for 15-loop planar, and 0.45 to 2.52 dB for 15-loop axial designs). Bandwidth (20 dB) shows quite stable performance across all loops, with variation of -0.05 to 2.49 MHz for planar and -0.6 to 1.56 MHz for axial designs but with increased reflections affecting the passband response. Evidently, axial designs demonstrate better loop failure tolerance as compared to planar designs. Finally, slight shrinkage/expansion in operating pass band was observed. In the future, we will validate these results during *in vivo* testing on human subjects.

References

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