

Resonator-enhanced radiating cable for UHF RFID readers

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Abstract
An antenna cable for enhancing and adjusting radio coverage is proposed. The presented solution is applied to the UHF RFID range of 866 MHz. With this leaky-wave antenna cable, radio coverage can be efficient and customizable. A 10 × 100 mm resonator patch is attached on an opening on the cable’s outer conductor to improve its radiating properties. The effect of its displacement is studied through simulations and measurements. The alignment affects both resonance frequency and signal strength. One resonator increases the radiated power by 2 dB (37%), multipliable by adding resonators. However, alignment accuracy of millimeters is needed in many cases. The greatest effect in both operating frequency and transmission loss magnitude comes from lifting the resonator from the cable’s surface, averagely being 7.6% and 8.6% per mm in measured operating frequency and linear magnitude of S21, respectively. Smallest changes are observed when moving the resonator along the cable, being 0.8% and 0.7% per mm, respectively.

KEYWORDS
coaxial, IoT, LCX, leaky-wave antenna, resonator

1 | INTRODUCTION

Leaky coaxial cables (LCX) can be used to enhance RF coverage in hard-to-reach places, such as in factories, Figure 1 (A). To enhance the cable’s RF properties various solutions have been presented.1–10 These include, for example, a mathematical approach to help suppressing all ineffective radiation harmonics in an LCX,7 while in another study, the shapes and sizes of slots in an LCX and their effect on radiating properties were investigated.2 A maximum read range of 0.6 m using a passive RFID tag with a 6.12 m long LCX with triangular slots on both sides of a meandering slot and with 0.25 W output power was also reported.5 Simulations and measurements were performed on a continuous, sinusoidally-modulated reactance surface on a coaxial cable and a hybrid solution with this kind of an antenna structure together with an LCX was proposed.4,5 This enables selective coverage by utilizing it as a distributed antenna system (DAS) in environments with different coverage requirements. The coupling loss of LCXs with periodically installed patches can be altered by the dimensions and periods of patches attached to it.5,7 A combination of stripline and coaxial type cable with slots was used within inspection counters for observing the absence/presence of RFID tags and a continuous “snake” type slot was found to be the best of the tested ones in terms of detecting tags in arbitrary directions.8 A solution with a long, thin metal bar acting as a near field antenna for tags placed along the bar was also reported.9 According to this publication, the proposed system was expected to be functional at over 30 m. In a corridor type space a 5.4 m long LCX in measuring RFID tags was demonstrated.10 Optimized RF coverage can be achieved by using resonators on the cable, with customizable locations, resulting in tunable radiation intensity along with it.

Detail of the LCX is shown in Figure 1(B), whereas the equivalent circuit is shown in Figure 1(C). Finite conductivity \( \sigma \) of the cable causes resistance \( R_1 \), current I creates inductance \( L_1 \), whereas conductance G and capacitance \( C_1 \) exists between the outer (ground) and the inner (signal) conductor. Adding a resonator on the coaxial cable with an opening (slot) creates capacitance \( C_2 \) between the cable (outer conductor) and the resonator. Finally, the resonator has resistance \( R_2 \), inductance \( L_2 \), and capacitance \( C_3 \). Changing the placement of the resonator chances the capacitance \( C_2 \).

This paper reports the effects of resonator’s alignment on the local RF radiation properties around the slot. This has also helped in finding the optimum placement of the resonator in research reported in an upcoming publication.11 In this article, the resonator is tuned for UHF RFID frequency of 866 MHz but can be selected depending on the application...
and used for other types of communication besides RFID. The effect of its alignment is studied through simulations and measurements.

2 | EXPERIMENTAL

A half-wavelength resonator was installed on top of a coaxial cable. The cable was a 1.2 m long closed coaxial cable, specifications in Table 1. The dielectric’s $\varepsilon_r$ was 1.29 in the characterized UHF range. The 1.1 mm thick jacket material’s $\varepsilon_r$ was 2.3. N-type connectors were attached to cable ends, and a 10 $\times$ 40 mm slot was made on the cable’s outer conductor one wavelength (305 mm in 866 MHz) away from the other end of the cable. Thereafter, a simple resonator, a 10 $\times$ 100 mm copper tape with a total thickness of 66 $\mu$m, was placed on top of the slot. Cable cladding was used to avoid the resonator shorting to the cable’s outer conductor (ground).

Finite integration technique (FIT) was used with time-domain simulation type in CST Microwave Studio 2019. To simplify the model and reduce simulation time, the corrugation was disregarded, and the outer conductor’s maximum diameter (13.9 mm) expressed in the datasheet was used instead. Waveguide port was used to initiate the correct propagation mode in the cable. Time domain simulations were run as parameter sweeps for cases representing different resonator alignments on top of the cable with hexahedral mesh and a minimum acceptable simulation accuracy of -40 dB, which resulted in reasonable convergence times without risking the simulation accuracy. Number of mesh cells ranged from 117,600 to 157,500, with highest mesh length of 11 mm. Mesh was finest in the vicinity of the resonator and slot. Also, finer mesh was tested with 1.5 million cells and highest mesh length of 4.1 mm, but it was found to yield comparable results to that with coarser mesh.

The measurement setup was constructed by attaching both ends of the cable under test in a vector network analyzer (VNA, Rohde&Schwarz ZVB-20). A jig made of low-permittivity and low-loss materials was used to carry the resonator in the vicinity of the slot. The resonator was bent to conform to the cable cladding’s circumference. To measure the change in RF response caused by the resonator displacements, it was moved as pointed out in Figure 1(B).

In order to observe behavior outside the UHF RFID band of 866 MHz, both measurements and simulations are presented at 700…1200 MHz with the exception of one simulation, for which results at a higher upper frequency are presented in order to show the RF behavior outside 1200 MHz. Due to the rigidity of the jig, for rotational type displacement (represented by blue arrows in Figure 1(B)) the resonator was lifted two millimeters from the cable surface.

### TABLE 1 Specifications for the coaxial cable

| Feature            | Value             |
|--------------------|-------------------|
| Inner conductor    | Cu-clad Al-wire, Ø4.8 mm |
| Dielectric         | Cellular polyethylene, Ø12.1 mm |
| Outer conductor    | Corrugated Cu-tube, Ømax13.9 mm |
| Jacket             | Ø16.0 mm          |
| Characteristic impedance | 50 $\Omega \pm 1$ $\Omega$ |
FIGURE 2  Response of different resonator displacement types on the S21 magnitude graph. (A) longitudinal displacement, simulation. (B) Longitudinal displacement, measurements. (C) elevational displacement, simulation. (D) Elevational displacement, measurements. (E) Rotational displacement, simulation. (F) Rotational displacement, measurements. (G) Cylindrical displacement, simulation. (H) Cylindrical displacement, measurements. (I) Effects of different resonator displacements on the operating frequency, combined. (J) Effects of different resonator displacements on the S21 mag minimum, combined [Color figure can be viewed at wileyonlinelibrary.com]
RESULTS

With a longitudinal displacement of the resonator, Figure 2(A),(B), moving its middle section from 50 mm before the middle of the slot to 50 mm past the slot, causes a clear shift in the resonance frequency. Before the middle section of the slot, there is a downshift in the operating frequency, whereas going past it results in an upshift in the frequency. The $S_{21}$ magnitude minimum stays in the same range until the very extreme position of $50 \text{ mm}$.

With elevational displacement, Figure 2(C),(D), increasing the elevation results in a positive frequency shift and decreasing transmission loss of the resonance peak.

With rotational displacement, Figure 2(E),(F), the simulations suggest an initial shift in resonance toward a lower frequency combined with higher transmission loss with a $5^\circ$ rotation, whereas rotating the resonator $10^\circ$ and onwards, this shift turns into the opposite direction. The resonator was lifted 2 mm above the cable to allow for rotational movement.

With cylindrical displacement, Figure 2(G),(H), the displacement has a rather uniform effect on both the frequency and the transmission loss.

Figure 2(I),(J) sum the results graphically. Elevational displacement has clearly the largest impact on both frequency and magnitude.

Table 2 summarizes the simulated and measured results and shows the effects of different movements of the resonator in resonance frequency and $S_{21}$ magnitude. The elevation has the largest effect both on resonance frequency, averaging 63.2 MHz per mm, and on $S_{21}$ magnitude, 0.311 dB per mm in measurements. The table also shows the calculated root

### Table 2

Collected results from simulations and measurements, calculated from initial (middle) versus extreme position of the resonator, and root mean square errors (RMSE) of simulations compared to different measurement points

|                         | Length | Elevation | Rotation$^a$ | Cylinder$^b$
|-------------------------|--------|-----------|--------------|----------------
|                          | MHz/ mm | dB/ mm    | MHz/ mm      | MHz/ mm        |
| Simulated average shift | 5.8    | 0.018     | 72.0         | 0.209          |
| Measured average shift  | 6.4    | 0.026     | 63.2         | 0.311          |
| Difference between simulation and measurement | 0.6    | 0.01     | 8.8          | 0.10           |
| RMSE (MHz or % in magnitude); simulation vs. measurement | 28.3 | 9.0 | 64.5 | 10.8 |

$^a$Rotational movement from the tip of the resonator in the middle plane; 1 mm corresponds to $1.15^\circ$ rotation. $^b$Cylindrical movement along the cladding of the cable. $^c$Up to $64^\circ$ instead of $72^\circ$ because at $72^\circ$ no deviation was observed in simulations. $^d$Up to $10^\circ$ instead of $45^\circ$ because at over $22.5^\circ$ no clear resonance peak could be observed in measured frequency range.

### Table 3

Difference of extreme position of the resonator compared to initial (middle) position

|                         | Length | Elevation | Rotation$^a$ | Cylinder$^b$
|-------------------------|--------|-----------|--------------|----------------
|                          | MHz   | $S_{21}$ dB/ mm | MHz   | $S_{21}$ dB/ mm | MHz   | $S_{21}$ dB/ mm | MHz   | $S_{21}$ dB/ mm |
|                          | Δ50mm | (min) Δ50mm    | Δ50mm | (min) Δ50mm    | Δ45° or 10° | (Δ5° or 10°) | Δ45° or 10° | (Δ5° or 10°) |
| Simulation              |       |              |       |              |       |              |       |              |
| Original value          | 839   | −1.278       | 839   | −1.278       | 1127  | −0.565       | 839   | −1.278       |
| Value at extreme       | 1130  | −0.363       | 1199  | −0.235       | 1409  | −0.256       | 983   | −0.229       |
| Δ                     | 292   | 0.915        | 360   | 1.043        | 283   | 0.308        | 144$^a$ | 1.049$^a$ |
| Measurement            |       |              |       |              |       |              |       |              |
| Original value          | 839   | −1.964       | 833   | −2.094       | 1071  | −0.914       | 839   | −2.102       |
| Value at extreme       | 1160  | −0.651       | 1149  | −0.536       | 1147  | −1.248       | 976   | −0.390       |
| Δ                     | 321   | 1.313        | 316   | 1.557        | 76.3$^b$ | 0.35$^b$     | 138   | 1.712 |

$^a$Up to $64^\circ$ instead of $72^\circ$ because at $72^\circ$ no deviation was observed. $^b$Up to $10^\circ$ instead of $45^\circ$ because at over $22.5^\circ$ no deviation was observed.

3 | RESULTS

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mean square errors (RMSE) between simulations and measurements. Table 3 shows the changes between initial and extreme positions of the resonator.

In a complementary simulation the number of slots and resonators was altered from the initial case. Four 10 × 40 mm slots with a repetition distance of one wavelength, 305 mm, were modeled on the outer conductor of a cable. The wavelength at 866 MHz was calculated using material and dimensional parameters provided in the cable manufacturer’s datasheet, Table 1 and Reference 12. The initial cable length was increased from 1.2 to 1.5 m in simulation in order to fit all slots in the setup. The distance of the slot center closest to the end of the cable was one period at both ends of the cable. Thereafter the number of resonators was changed from zero to four. Figure 3(A) shows one of the simulated situations, with four slots and two resonators. The effect per one consecutively added resonator-slot pair is about one decibel, Figure 3(B), with \( S_{21} \) magnitude minimum at around 866 MHz, changing from −1.9 dB…−4.8 dB with 305 mm repetition distances (1–4 resonators, respectively). The simulations show the behavior to be uniform. This was also seen in the balance graph. Its minimum with one resonator and slot, 0.83, changed into a minimum of 0.72 with four resonators and slots, thus pointing out that the behavior is due to increasing signal loss between the ports, that is, power being increasingly radiated. In yet unpublished work, the authors performed simulations with up to 20 resonators on the LCX, suggesting uniform behavior even with a higher amount of resonator-slot pairs.11

4 CONCLUSIONS

An enhanced ½” antenna cable with a 10 × 100 mm resonator structure on top of a 10 × 40 mm slot in its outer surface was characterized through simulations and measurements. Four displacement types of the resonator were tested. These included longitudinal, elevational, rotational, and cylindrical displacements from its initial placement directly on top of the slot in the cable’s outer conductor. This shows how different misalignment types can affect the cable’s radiating properties, helping in achieving optimal placements of resonators, resulting in increased performance compared to a LCX with continuous opening on its side.

Lifting the resonator off from the cable surface had the most distinguishable effect on both resonance frequency and its magnitude. One-mm elevation resulted in an average shift of 7.6% and 8.6% in measured resonance frequency and signal magnitude, respectively. This resulted in degrading performance in the RFID frequency of 866 MHz.

When using multiple resonator-opening pairs, radiated power was increased by 1 dB/resonator on average. In an ideal case, the cable’s radiating properties could be customized either during assembly or in the field.

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