

Experimental assessment of RFID and IEEE 802.15.4 physical-layer performance for radio positioning and data transmission in facilities equipped with ballistic shields and anti-ricochet linings

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ABSTRACT

The implementation of precise positioning and communication systems intended for advanced combat simulators encounters limitations associated in particular with the presence of specialized construction materials affecting radio wave propagation. These include, most notably, steel ballistic shields and polymer-rubber anti-ricochet linings. This article presents the results of comprehensive experimental research aimed at verifying the feasibility of using RFID technology in the HF (13.56 MHz) and UHF (866 MHz) bands for localization, as well as the IEEE 802.15.4 standard (2.4 GHz) for data transmission in such an environment. The analysis encompasses an assessment of range, the effect of tag orientation changes, and system power consumption, and - constituting a key aspect of this work – a quantitative investigation of the impact of the two most commonly used types of anti-ricochet linings (with thicknesses of 44 mm and 47 mm, characterized as lossy dielectrics) on the performance of radio systems, with particular emphasis on near-field phenomena. This work provides quantitative data on the insertion loss of the investigated materials and on the two-port impedance parameters (Z_{11} , Z_{22} , Z_{12}) that describe the near-field coupling between antennas separated by the lining, together with concepts for dedicated power supply systems. The main novelty lies in the first systematic, single-campaign characterization of how anti-ricochet linings modify near-field coupling and insertion loss across the HF, UHF, and 2.4 GHz bands used simultaneously in such facilities. The results contribute to the understanding of the limitations and possibilities of implementing radio systems in demanding indoor environments and may serve as a basis for designing integrated radio systems intended for advanced combat simulators.

Keywords: RFID, indoor positioning system (IPS), near field, UHF, HF, IEEE 802.15.4, radio wave attenuation, insertion loss, anti-ricochet lining, lossy dielectric, mutual coupling, Virtual Combat Simulator, power management, electromagnetic compatibility.

INTRODUCTION

The development of advanced Virtual Combat Simulators imposes high demands on the supporting radio systems employed within them, which must enable precise tracking of

the position of personnel, trainees, and objects, as well as ensure reliable real-time data transmission. These challenges are intensified in the case of facilities designed for live-fire exercises, where an extensive system of ballistic shields and anti-ricochet wall and floor linings

is utilized. There is a noticeable lack of literature addressing the impact of such elements on radio wave propagation. This work aims to fill this gap through a systematic evaluation of the applicability of selected, widely available radio technologies in live-fire shooting range rooms. The analysis covers radio frequency identification (RFID) technology in the HF (13.56 MHz) and UHF (866 MHz) bands, as well as the IEEE 802.15.4 wireless communication standard (2.4 GHz). The research presented in this paper focuses on the practical aspects of implementation and the quantitative assessment of the impact of the ballistic linings used on such radio-transmission parameters as achievable range, read rate, and power consumption. The tests were conducted on commonly used bullet-trapping and anti-ricochet plates in the form of compression-molded polymer-rubber panels measuring 500×500 mm: type 1 panels with a protective top layer (total thickness 47 mm) and type 2 panels without the protective layer (total thickness 44 mm). Both types of panels were identified as materials exhibiting the characteristics of lossy dielectrics. Particular attention was paid to the phenomena occurring in the near field of the antennas, which are fundamental to the operation of short-range RFID systems and can significantly affect the interaction of antennas with their surroundings, even in systems designed for operation at greater distances.

The main contribution and novelty of this work are threefold. First, to the best of the authors' knowledge, this is the first study to quantify – within a single, coherent measurement campaign – the insertion loss and near-field coupling introduced by anti-ricochet ballistic linings across the three candidate radio bands (13.56 MHz, 866 MHz, and 2.4 GHz) considered for positioning and data transmission in live-fire simulator rooms. Second, the work provides measured two-port impedance parameters (Z_{11} , Z_{22} , Z_{12}) that explain, on a physical basis, the counter-intuitive negative insertion loss (apparent gain) observed at 866 MHz. Third, it derives concrete engineering recommendations – including antenna type, polarization, duty cycle, and power-budget guidance – directly applicable to the design of an integrated, on-body radio subsystem. In practical terms, the results allow a system designer to select the band and antenna configuration to adopt, to bound the expected signal margin

when a reader must operate above a lining-covered floor, and to size the battery for a required operating time. The experimental results are intended to provide specific engineering data and practical recommendations for designers of radio systems operating in complex and demanding indoor environments.

STATE OF THE ART

This section reviews the state of the art relevant to the three pillars of the present study: (i) RFID-based positioning and the distinction between near- and far-field operation, (ii) the interaction of radio waves with construction and lossy-dielectric materials in the near field, and (iii) low-rate wireless communication together with its coexistence and power-management aspects. Recent surveys confirm that indoor positioning remains an active field in which RFID competes and cooperates with Wi-Fi, Bluetooth Low Energy, and ultra-wideband solutions [1, 2].

RFID technologies in positioning systems: Near field vs. far field

RFID technology is widely used in localization systems. The HF band (e.g., 13.56 MHz) operates on the principle of inductive coupling in the near field, where the range is limited to a fraction of a wavelength, but these systems may be less sensitive to certain aspects of the propagation environment [3]. On the other hand, UHF RFID systems (860–960 MHz) are designed for far-field operation [4], which enables greater ranges; however, they are more susceptible to multipath reflections and attenuation [5]. In the immediate vicinity of a UHF antenna (near field), the field characteristics are complex, and phenomena such as a strong dependence on tag orientation become dominant [6]. Localization algorithms are commonly based on received signal strength indicator (RSSI) measurement or phase analysis [7, 8], and are increasingly combined with fingerprinting and machine-learning post-processing [9, 10]. Reader-antenna design also strongly influences performance, both for far-field range and for controlled near-field interrogation volumes [11–13].

Influence of materials on radio wave propagation and near-field phenomena

Construction materials significantly affect the propagation of electromagnetic waves [14, 15]. In the near field of an antenna, the presence of dielectric or conductive materials can alter its impedance and radiation characteristics; this sensitivity is well documented for tags mounted on, or placed near, dielectric and metallic objects [16–19]. The analysis of insertion loss caused by specialized materials, such as anti-ricochet linings, is therefore crucial for the design of systems in atypical environments [20]. These linings, often made of rubber, elastomers, or polymer composites (non-conductive or weakly conductive materials), behave as lossy dielectrics. Their influence on radio waves depends on the complex electric permittivity, Equation 1:

$$\epsilon = \epsilon' - j\epsilon'' \quad (1)$$

where: ϵ'' – represents dielectric losses, and on the magnetic permeability, Equation 2:

$$\mu = \mu' - j\mu'' \quad (2)$$

where: μ'' represents magnetic losses, usually negligible for non-metallic anti-ricochet materials.

Losses in the dielectric lead to the absorption of electromagnetic-wave energy and its conversion into heat. Additionally, at the boundary of media with different wave impedances (which depend on ϵ and μ), reflection and refraction of the wave occur. The ratio of the material thickness to the wavelength in that material is decisive for interference and resonance effects. This resonance mechanism is central to the results, where the lining thickness is shown to be comparable to a quarter-wavelength in the material.

IEEE 802.15.4 wireless communication systems

The IEEE 802.15.4 standard forms the basis for energy-efficient wireless personal-area networks [21], operating in the far field. Because it shares the crowded 2.4 GHz ISM band with Wi-Fi and Bluetooth, coexistence and cross-technology interference are recurring concerns [22]. Experimental studies typically quantify robustness through the packet error rate (PER) as a

function of interferer power, channel offset, and offered load; in general, a modest frequency offset between the interferer and the low-rate link substantially reduces PER, whereas heavier interferer traffic and larger frames degrade it. These findings motivate the interference test, in which a high-power UHF RFID reader acts as the aggressor for the 2.4 GHz link. As indicated by Raghunathan et al. [23], efficient energy management is decisive for battery-powered mobile devices. This requires the analysis of the current consumption of the components in their various operating modes and the design of efficient power-supply and charging systems. In the present application the reader is intended to be worn by the user and powered from a Li-Po battery, so the current profile of the UHF reader and its dependence on output power and duty cycle directly determines the achievable operating time.

MATERIALS AND METHODS

All experimental tests were conducted under laboratory conditions, striving to reproduce the key aspects of the target operating environment. The anti-ricochet linings, constituting a key element of the simulator environment, were represented by two types of panels measuring 50×50 cm: type 1 (with a protective top layer, total thickness 47 mm) and type 2 (without the protective top layer, total thickness 44 mm). Based on the results of the attenuation tests, the material of these linings was identified as a lossy dielectric. Where a lining thickness of “4 cm” is quoted for individual UHF RFID tests, it refers to the type 2 lining (44 mm). The following subsections describe, in turn, the evaluation of the two RFID bands, the evaluation of the IEEE 802.15.4 module, the power-supply design, the attenuation measurements, and the measurement equipment and uncertainty.

Evaluation of RFID Systems

The evaluation of the RFID subsystems was carried out separately for the two candidate bands, since they rely on fundamentally different coupling mechanisms – inductive (magnetic) near-field coupling at 13.56 MHz and predominantly far-field radiation at 866 MHz – and therefore call for different measurement setups and figures of merit.

RFID Technology in the HF Band (13.56 MHz) – Near-field operation

The study of the 13.56 MHz RFID system, based on inductive coupling in the near field, used the ST25R3911B-DISCO evaluation kit together with ST25TA64K and ST25STA02K tags. The range, being a function of the coil geometry and the magnetic-field strength, was analysed. The axial magnetic-field strength H_z along the Z-axis of a rectangular coil (of side lengths a and b , N turns, carrying current I) at a distance z was described by Equation 3:

$$H_z(z) = \frac{NI}{\pi} \frac{ab}{\sqrt{a^2 + b^2 + 4z^2}} \left(\frac{1}{a^2 + 4z^2} + \frac{1}{b^2 + 4z^2} \right) \quad (3)$$

where: H_z is the axial magnetic-field strength (A/m), N is the number of turns (dimensionless), I is the coil current (A), a and b are the side lengths of the rectangular coil (m), and z is the distance measured along the coil axis, i.e., the Z-axis normal to the plane of the coil (m).

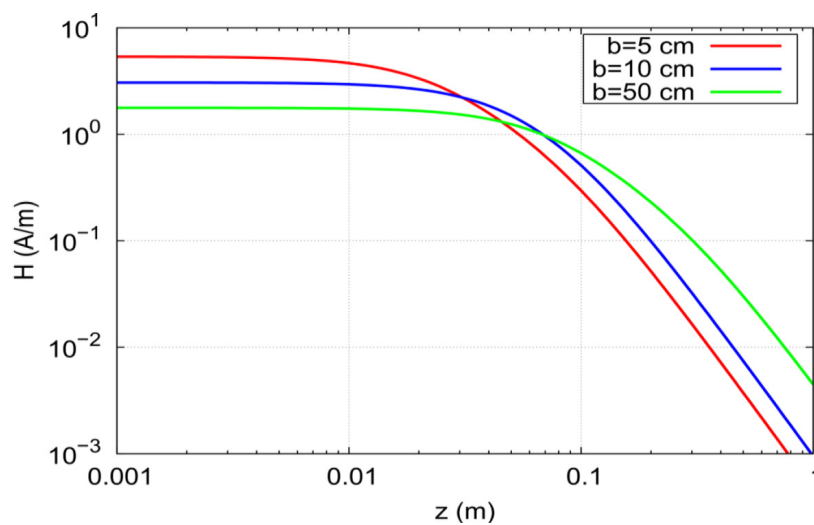


Figure 1. Change in magnetic-field strength with increasing axial distance z along the coil axis, for various coil dimensions b (fixed $a = 15$ cm, $N = 2$, $I = 200$ mA)
The horizontal axis is the axial distance z (see Equation 3)

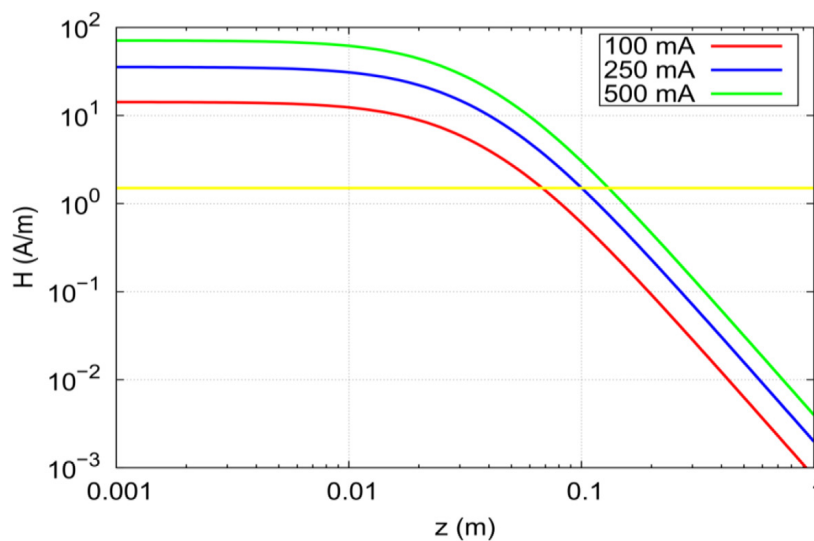


Figure 2. Change in magnetic-field strength with increasing axial distance z along the coil axis, for various current intensities I (fixed $a = 5$ cm, $b = 8$ cm, $N = 10$)
The horizontal axis is the axial distance z (see Equation 3)

Accordingly, the horizontal axis of the curves in figures (Figure 1 and Figure 2) is this axial distance z . Tag activation occurs for H in the range 1.5–7.5 A/m. The tests involved placing the tags under the aforementioned anti-ricochet linings of type 1 or type 2, a view of which is presented in Figure 3.

RFID technology in the UHF band (866 MHz) – Near-field and far-field aspects

The M6e ThingMagic reader with an MT-242025/TRH/A/A panel antenna and a reference half-wave dipole antenna, together with 22 types of tags, were tested in the EU3 band (865.6–867.6 MHz), as shown in (Figure 4). The RSSI was analysed as a function of tag orientation

(angle θ from 0 to 180 degrees), particularly in the near field of the antenna, as well as the range (up to 35 cm in the detailed tests, and at greater distances in the general tests) in the presence of an anti-ricochet lining (type 2, 44 mm), on which the tag was placed. Read-rate measurements (averaged over a 30 s period) and power-consumption measurements (for various RF_on/RF_off cycles) were carried out for different reader output-power configurations (up to 31.5 dBm).

Evaluation of the radio communication module (IEEE 802.15.4)

Tests of the EFR32MG12 system (MGM12P module) on the BRD4304A and Thunderboard™ Sense 2 kits included range measurements

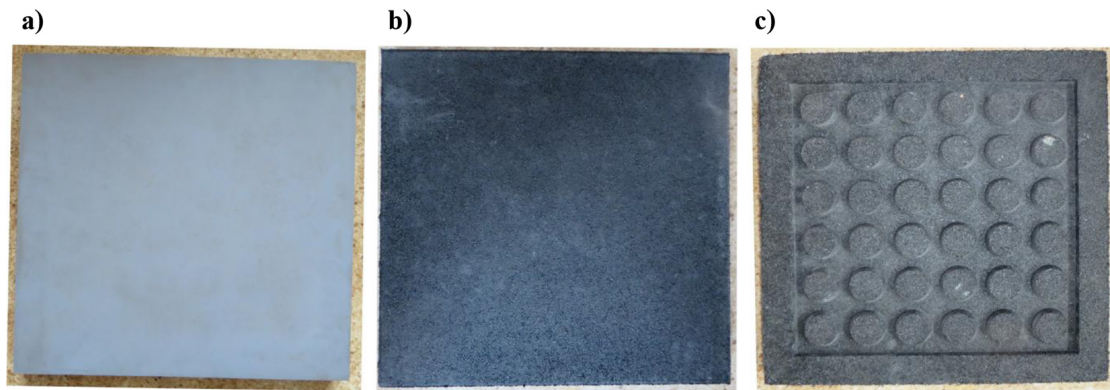


Figure 3. Anti-ricochet lining: (a) type 1, top view; (b) type 2, top view; (c) bottom view (type 1 and type 2)



Figure 4. Photograph of the ThingMagic M6e reader module

(indoors and in open space) in the far field, as well as the packet error rate (PER, for 16-byte packets) in the presence of interference from the M6e-Nano UHF RFID reader (power 27 dBm, distance 20 cm). The rationale for the 16-byte payload, and the expected behaviour under larger payloads and heavier load. The test software (C, Simplicity Studio) enabled configuration of the transmitter power, the data rate (up to 2000 kbps), and the packet-transmission frequency.

The energy requirements for the EFR32MG12 (3.3 V, 75 mA) and the Impinj RS500 reader (5 V/500 mA or 3.6 V/550 mA) were analysed. Power-supply concepts based on the LTC3566 (with an LDLN030 LDO) and LTC3586 circuits from Analog Devices were proposed, assuming 3 hours of operation from a Li-Po battery of approximately 3000 mAh.

Investigation of radio wave attenuation by anti-ricochet linings – near-field and far-field interactions

Insertion loss (IL) at 13.56 MHz and 866 MHz was measured using a PNA-L N5230A

vector network analyzer with loop antennas (13.56 MHz) and with short and half-wave dipoles (866 MHz). The tests employed anti-ricochet linings of types 1 and 2, which were placed between the transmitting and receiving antennas at a controlled distance d . A diagram of the measurement setup is presented in Figure 6. For 866 MHz, with close antenna placement (separation $e = 20$ cm), the coupling in the near field and its modification by the lining were analysed. The two-port network formed by the two antennas and the interposed lining was fully characterized by its scattering matrix; the insertion loss follows from the transmission coefficient S_{21} , while the coupled-antenna behaviour is expressed through the equivalent two-port impedance parameters Z_{11} , Z_{22} , and Z_{12} ($= Z_{21}$). These parameters, and the derived input impedances and standing-wave ratios (Tables 1–4 and Figure 5).

Measurement equipment and uncertainty

All radio-frequency measurements were performed with calibrated laboratory instruments. Insertion loss and the two-port parameters were

Table 1. Impedance-model parameters of the two-short-dipole system at 866 MHz (values in Ω)

Configuration	Z_{11} (Ω)	Z_{22} (Ω)	$Z_{12} = Z_{21}$ (Ω)
No lining	21.64 – j53.23	2.30 – j20.70	0.32 + j0.25
$d = 1$ cm	29.73 – j46.75	2.48 – j20.85	0.19 – j0.22
$d = 3$ cm	24.85 – j51.23	2.51 – j20.60	0.17 – j0.16
$d = 5$ cm	23.66 – j52.43	2.47 – j20.50	0.16 – j0.15
$d = 7$ cm	23.22 – j52.80	2.25 – j20.45	0.15 – j0.18
$d = 9$ cm	23.10 – j53.00	1.96 – j20.60	0.15 – j0.20
$d = 11$ cm	23.12 – j53.10	2.09 – j20.62	0.12 – j0.27
$d = 13$ cm	23.10 – j53.40	2.06 – j20.71	0.13 – j0.27
$d = 15$ cm	22.90 – j53.60	2.17 – j20.72	0.08 – j0.29

Table 2. Impedance-model parameters of the two-half-wave-dipole system at 866 MHz (values in Ω)

Configuration	Z_{11} (Ω)	Z_{22} (Ω)	$Z_{12} = Z_{21}$ (Ω)
No lining	33.76 – j18.00	45.05 + j5.66	7.78 – j5.40
$d = 1$ cm	58.34 – j9.00	41.30 + j8.20	4.73 – j12.10
$d = 3$ cm	40.20 – j6.30	44.17 + j3.91	–2.70 – j10.92
$d = 5$ cm	40.20 – j14.00	52.60 + j2.97	–4.25 – j9.91
$d = 7$ cm	37.31 – j17.80	59.10 + j7.38	–4.06 – j10.30
$d = 9$ cm	34.74 – j19.53	58.63 + j13.30	–2.70 – j9.74
$d = 11$ cm	30.38 – j19.10	54.62 + j21.58	–0.57 – j10.31
$d = 13$ cm	29.07 – j17.23	59.39 + j19.20	0.08 – j11.00
$d = 15$ cm	28.76 – j15.60	77.36 + j6.44	–2.82 – j11.92

Table 3. Input impedance and voltage standing-wave ratio in the feed lines of the short dipoles at 866 MHz (impedances in Ω)

Configuration	ZIN1 (Ω)	ZIN2 (Ω)	VSWR1	VSWR2
no lining	21.68 – j53.20	2.31 – j20.70	5.16	25.35
d = 1 cm	29.75 – j46.74	2.47 – j20.81	3.45	23.77
d = 3 cm	24.85 – j51.22	2.54 – j20.62	4.39	23.08
d = 5 cm	23.63 – j52.44	2.48 – j20.52	4.70	23.60
d = 7 cm	23.28 – j52.79	2.28 – j20.48	4.80	25.57
d = 9 cm	23.19 – j52.95	2.19 – j20.52	4.83	26.64
d = 11 cm	23.18 – j53.13	2.09 – j20.63	4.85	27.94
d = 13 cm	23.15 – j53.36	2.07 – j20.73	4.88	28.35
d = 15 cm	22.95 – j53.61	2.21 – j20.66	4.94	26.50

Table 4. Input impedance and voltage standing-wave ratio in the feed lines of the half-wave dipoles at 866 MHz (impedances in Ω)

Configuration	ZIN1 (Ω)	ZIN2 (Ω)	VSWR1	VSWR2
No lining	33.49 – j17.14	44.36 + j6.57	1.77	1.21
d = 1 cm	59.46 – j10.31	42.69 + j7.24	1.29	1.25
d = 3 cm	41.35 – j7.00	45.45 + j3.33	1.27	1.12
d = 5 cm	40.92 – j14.81	53.54 + j2.19	1.46	1.08
d = 7 cm	38.12 – j18.61	60.26 + j6.75	1.65	1.25
d = 9 cm	35.48 – j20.10	59.75 + j12.94	1.79	1.34
d = 11 cm	31.63 – j19.40	55.90 + j21.74	1.93	1.53
d = 13 cm	30.15 – j17.40	60.85 + j19.54	1.95	1.50
d = 15 cm	29.78 – j16.18	79.17 + j5.90	1.93	1.60

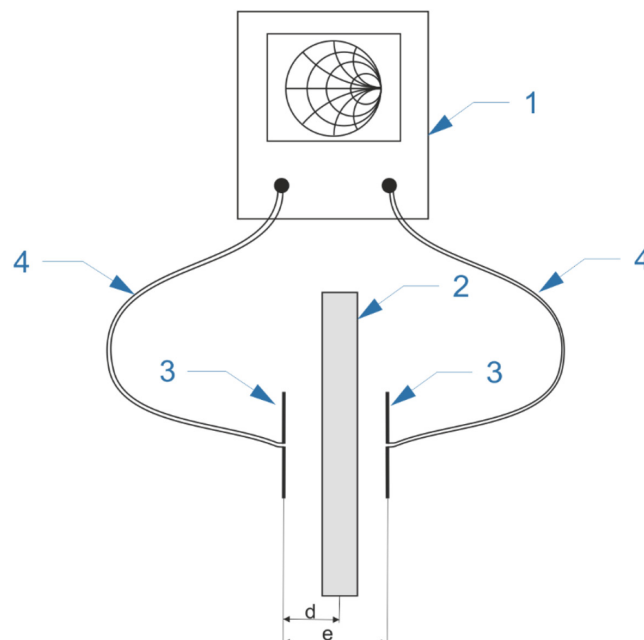


Figure 5. Diagram of the measurement setup for determining the insertion loss of the anti-ricochet linings (type 1 and type 2) with the PNA-L N5230A analyzer

The numbered items are: (1) the two-port vector network analyzer; (2) coaxial feed cables; (3) the two measurement antennas separated by distance e ; (4) the anti-ricochet lining under test, inserted at distance d from the first antenna

measured with a PNA-L N5230A vector network analyzer, two-port SOLT-calibrated over the bands of interest; after such a calibration the transmission-magnitude uncertainty of this class of instrument is typically of the order of ± 0.1 – 0.2 dB in this frequency range. The spectral and time-domain characteristics of the UHF reader were recorded with a Rohde and Schwarz FSV30 signal analyzer, and the current-consumption measurements were obtained with a Tektronix DMM 4040 multimeter together with a Tektronix DPO 7054 oscilloscope, the pulsed reader current being averaged across the measurement window. The RSSI values reported by the M6e reader have a resolution of approximately 1 dB, which sets the practical uncertainty of the RSSI-versus-distance and RSSI-versus-orientation results. Read-rate and current figures were averaged over a 30 s window per operating point, and representative points were re-measured to confirm repeatability; the run-to-run spread was small compared with the reported effects. At 13.56 MHz the insertion loss is a small quantity, obtained as the difference of two low and nearly equal power levels, so the measured trace is dominated by noise; for this reason the 13.56 MHz insertion-loss result is reported as a mean value (≈ 0.35 dB) together with the observed maximum (< 0.6 dB) rather than as a smooth curve. A full statistical treatment (repetition counts, confidence intervals, and significance testing), together with a direct dielectric characterization of the linings, was beyond the scope of the present feasibility campaign and is identified among the directions for further work.

RESULTS AND DISCUSSION

This section presents the experimental results for each subsystem and then discusses their implications for the target positioning and data-transmission system. For clarity, within each subsection the measured results are stated first and their physical interpretation is given afterwards, so that the presentation of the data is kept separate from its interpretation.

Evaluation of RFID systems for positioning purposes

The two RFID bands are assessed in turn against the requirements of the positioning

system: sufficient range, tolerance to tag and coil orientation, an acceptable read rate, and a manageable power consumption.

RFID Technology in the HF band (13.56 MHz) – Near-field limitations

Results. The 13.56 MHz RFID system, based on inductive coupling in the near field, demonstrated a maximum range of 110 mm with an ideal, parallel coil orientation. Even a slight deviation from the optimal orientation led to a complete loss of readout. The anti-ricochet lining (both type 1, 47 mm, and type 2, 44 mm) had a minimal effect on the range (a difference of approximately 0.5 cm). A sufficient read rate was obtained (e.g., 351 reads per 30 s for a single tag in continuous mode).

Interpretation. These observations are consistent with expectations for a technology whose operation relies on maximizing magnetic-flux linkage, and for which the magnetic-field strength drops sharply with distance. The negligible effect of the lining indicates that the tested materials, being lossy dielectrics, do not significantly disturb the near magnetic field at this frequency: the wavelength for 13.56 MHz is approximately 22 m, so the lining thickness (4–5 cm) is electrically very small ($\ll \lambda$), which explains the negligible impact on the dominant magnetic coupling. Despite the sufficient read rate, the extremely short range and the critical sensitivity to orientation render this technology impractical for the intended positioning system.

RFID Technology in the UHF band (866 MHz) – Near-field and far-field challenges

Results. UHF RFID systems operating in the far field achieved ranges of up to 3 m (panel antenna, 27 dBm, without lining). In the near field of the antenna, tag orientation was critical, causing RSSI variations of up to 25 dB for the dipole antenna and approximately 6 dB for the panel antenna. The anti-ricochet lining (type 2, 44 mm) introduced an average attenuation of about 11 dB, reducing the effective range. The current drawn by the M6e reader reached 1.2 A at 31.5 dBm, but could be reduced substantially through the RF_on/RF_off duty cycle (e.g., to 210 mA at 100 ms ON / 900 ms OFF). The read rate was approximately 17 reads/s/tag for 5 tags in continuous mode.

Interpretation. The far-field range is promising for certain scenarios, but the strong dependence on tag orientation in the near field – associated with the complex field structure in that zone – means that the panel antenna's lower sensitivity is preferable. The average 11 dB attenuation introduced by the lining is consistent with general observations on the influence of dielectric materials on UHF wave propagation [14, 16, 24, 25]. The proximity of the human body, as a lossy medium, can further degrade the signal in the near field of the antenna. The read rate is adequate, and the current consumption can be managed by the duty cycle. UHF technology is therefore conditionally useful, requiring careful antenna design (directional pattern, circular polarization) and consideration of environmental effects.

Radio communication module (IEEE 802.15.4)

Results. The EFR32MG12 module, operating in the far field, demonstrated a range of > 100 m outdoors and > 15–20 m indoors (at a power of -7 dBm), which exceeds typical requirements for simulators. The interference from the UHF RFID reader (866 MHz, 27 dBm, at a distance of 20 cm) had only a minor impact on the PER of the 2.4 GHz system, which increased from 2% to 2.2% for 16-byte packets.

Interpretation. This small increase suggests good coexistence of the two systems. The 16-byte payload was chosen deliberately: it is representative of the compact telemetry and positioning-beacon messages the data link is expected to carry and, because the fixed physical-layer preamble and header then dominate the frame, it constitutes a conservative (worst-case) test of header and preamble robustness under interference. It should be noted, however, that a short frame also occupies the channel only briefly, so the probability of overlap with the periodic bursts of the 27 dBm UHF reader is correspondingly low. Under heavier network load, or with substantially larger payloads, the on-air time per frame grows, the collision cross-section with the reader's transmit windows increases, and the PER can be expected to rise beyond the small increment observed here. A quantitative assessment of PER as a function of payload length and offered load, and under multiple simultaneous interferers, is therefore

recommended as part of the further verification identified below.

Power-supply module design

The proposed power-supply concepts (LTC3566 + LDO, or LTC3586) are well matched to the identified load profiles (EFR32MG12: 3.3 V/75 mA; RS500: 5 V/500 mA or 3.6 V/550 mA) and offer high efficiency together with integrated charge management for a Li-Po battery of approximately 3000 mAh. Because the reader's average current is a near-linear function of the RF_on/RF_off duty cycle, the required battery capacity for a target operating time can be estimated directly from the duty-cycle setting.

Radio wave attenuation by anti-ricochet linings – the role of the near field

Results (13.56 MHz). In the 13.56 MHz band, where magnetic coupling in the near field dominates, the influence of the anti-ricochet linings (types 1 and 2) was negligible, with IL < 0.6 dB (mean $\approx$ 0.35 dB). This confirms the weak interaction of the magnetic field with this type of lossy dielectric at this frequency and the small electrical thickness of the material.

Results (866 MHz). At 866 MHz the influence of the linings is significant and complex. The insertion loss ranged from about -1 dB (apparent gain) to about 5.5 dB (attenuation), depending on the antenna type and on the lining distance d . The insertion loss varied with d with a spatial period of about 8 cm, indicating a standing wave between the lining and the antennas. Type 1 lining (with the protective layer) generally introduced approximately 0.5 dB greater attenuation than type 2. For the short-dipole configuration the insertion loss remained positive throughout ($\approx 4.5 \pm 0.5$ dB), whereas for the half-wave-dipole configuration it took values from about -1 dB to about 1.5 dB.

To substantiate the impedance-based explanation and to provide the quantitative frequency-domain characterization of the coupled-antenna case, the measured two-port impedance parameters at 866 MHz are reported in Tables 1–4 and in (Figure 6). Tables 1 and 2 give the self- and mutual impedances (Z_{11} , Z_{22} , $Z_{12} = Z_{21}$) for the short-dipole and half-wave-dipole configurations, respectively, as the lining is moved away from the first antenna (distance d), together with the reference case without a lining. Tables 3 and 4 give the

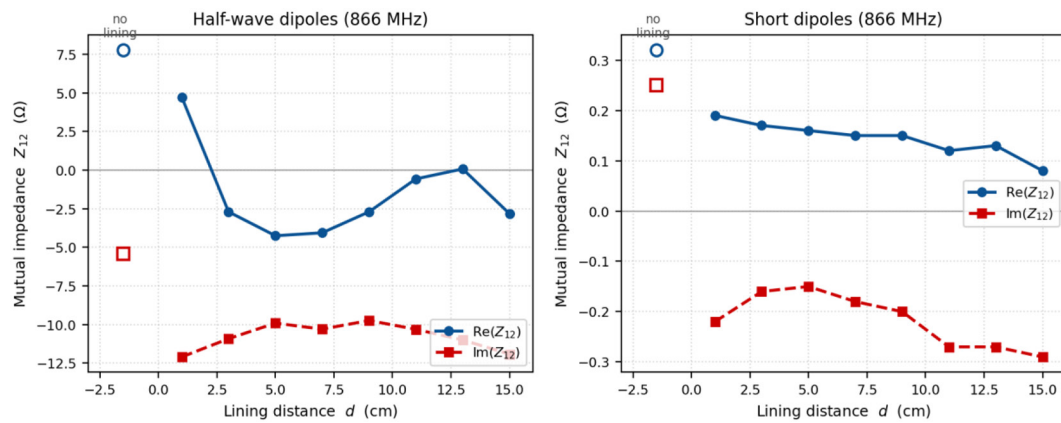


Figure 6. Real and imaginary parts of the mutual impedance Z_{12} ($= Z_{21}$) at 866 MHz as a function of the lining distance d , for the half-wave-dipole (left) and short-dipole (right) configurations. Open markers denote the reference case without a lining. For the half-wave dipoles the real part of Z_{12} changes sign, which is correlated with the sign change (and the negative values) of the insertion loss

resulting input impedances (Z_{IN1} , Z_{IN2}) seen at the two feed ports and the corresponding voltage standing-wave ratios (VSWR).

Interpretation. For the short dipoles, whose input impedance is strongly capacitive, the real part of Z_{12} remains small and positive and varies only weakly with d (Table 1, Figure 6 right), consistent with the uniformly positive insertion loss ($\approx 4.5 \pm 0.5$ dB) observed for that configuration. For the half-wave dipoles, which operate close to resonance, both the self-impedances and the mutual impedance vary strongly with d ; in particular, the real part of Z_{12} changes sign (Table 2, Figure 6 left). This sign change is correlated with the sign change of the insertion loss: at the distances where $\text{Re}(Z_{12})$ becomes negative, the power delivered to the load of the second antenna exceeds that of the lining-free reference, which is the origin of the apparent gain (negative insertion loss down to about -1 dB). These impedance parameters can be converted directly to the corresponding scattering parameters (S_{11} , S_{22} , S_{21}) through the reference impedance $Z_0 = 50 \Omega$, so Tables 1–4 and (Figure 6) provide the magnitude-and-phase characterization of S_{21} / Z_{12} that quantifies the near-field mutual coupling and its modification by the dielectric lining. Consistently, the input-impedance and VSWR data (Tables 3 and 4) show that the largest impedance changes occur when the lining is placed immediately next to a resonant (half-wave) antenna, while for the capacitive short dipoles the input impedance is only weakly perturbed.

Effective permittivity of the lining. The measurements also allow a first-order estimate of the effective relative permittivity of the linings. The

spatial period over which the 866 MHz insertion loss cycles between its maximum and minimum is about 8 cm, i.e., one quarter of the free-space wavelength ($\lambda_{\text{air}} \approx 34.6$ cm), confirming that reflection at the air–lining interface governs the effect. Interpreting the physical lining thickness (44–47 mm) as approximately one quarter-wavelength in the material gives $\lambda_{\text{material}} \approx 176\text{--}188$ mm and hence an effective relative permittivity $\epsilon_r \approx (\lambda_{\text{air}} / \lambda_{\text{material}})^2 \approx 3.4\text{--}3.9$, a value typical of rubber-like polymer composites. The magnetic losses are negligible (the material is non-magnetic), whereas the electric loss tangent is non-zero but moderate, consistent with the modest insertion loss observed. A precise determination of ϵ_r and $\tan \delta$ (for example, with an open-ended coaxial-probe technique) was not performed here and is left for further work. Improper antenna placement relative to the lining can result in a bidirectional signal drop of approximately 10 dB, which must be taken into account in the link budget.

CONCLUSIONS

The conducted research provides a comprehensive assessment of the feasibility of employing RFID and IEEE 802.15.4 technologies in the specific environment of a virtual simulator, taking into account the influence of anti-ricochet materials and near-field phenomena. The principal conclusions are as follows.

- RFID 13.56 MHz (HF) technology, based on coupling in the strict near field, is unsuitable for a positioning system in the considered

application because of its extremely short range (max. 110 mm) and its critical sensitivity to coil orientation.

- RFID UHF (866 MHz) offers a potentially sufficient range (up to several metres); however, its efficacy is strongly diminished by the anti-ricochet linings (average attenuation of about 11 dB) and it is sensitive to tag orientation, particularly in the near field of the antenna (RSSI variations of up to 25 dB). The application of this technology requires advanced antenna solutions and careful planning of component placement.
- IEEE 802.15.4 (EFR32MG12) is recommended for the data-exchange system, demonstrating an adequate range (> 100 m outdoors) and good immunity to interference from the UHF RFID system (PER increased only from 2% to 2.2% for 16-byte packets under the tested conditions).

The anti-ricochet linings (types 1 and 2), being lossy dielectrics with an estimated effective permittivity $\epsilon_r \approx 3.4\text{--}3.9$, have a negligible effect on the near magnetic field at 13.56 MHz (IL < 0.6 dB) but significantly modify UHF wave propagation at 866 MHz, including the near-field mutual coupling between coupled antennas, as quantified by the two-port impedance parameters.

The tests were conducted under laboratory conditions using commercially available components. In particular, the experiments did not evaluate several realistic operational factors: the dynamic presence and movement of the human body on which body-worn antennas are mounted; the simultaneous operation of multiple users and tags; reflections and multipath from the actual shooting-range infrastructure (steel ballistic shields, walls, and floor); and changes in environmental conditions during operation. The electromagnetic properties of the linings (relative permittivity and loss tangent) were estimated from the measured quarter-wave behaviour rather than measured directly, and the results are reported primarily in a descriptive form without a full statistical treatment (repetition counts, confidence intervals, or significance tests). These aspects define the boundaries within which the present conclusions hold and motivate the directions for further research.

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