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RFID over Low Cost VCSEL-based MMF Links: Experimental Demonstration and Distortion Study

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Abstract: Radio-over-Fibre (RoF) Distributed Antenna System (DAS) technology has been investigated for the distribution of ultra-high frequency (UHF) radio frequency identification (RFID) signals. RoF DAS allows for reduced number of readers and centralized placement of readers which facilitates easy system maintenance, but it is important to find a low-cost solution that can achieve comparable performance to a conventional RFID system. In this work, a low-cost vertical-cavity surface-emitting laser (VCSEL)-based multimode fibre (MMF) link has been developed and demonstrated for passive UHF RFID applications. The reported results show almost the same performance when compared with a conventional RFID system. In addition, simple spatial antenna diversity schemes are tested, with improved performance reported in comparison with a RFID-RoF system without diversity. Also, an investigation of RFID over fibre with RoF nonlinearity is carried out showing that PR-ASK RFID modulation allows for higher levels of RF carrier and modulated signal power than the ASK RFID, for low levels of nonlinearity.

1. Introduction

UHF RFID (ultra-high frequency radio frequency identification) represents a radio transponder backscatter system that often features active readers and passive tags. The tag transponders contain unique identification codes which, together with other relevant information, are modulated onto the backscattered signals. RFID tags may be active, battery assisted and passive depending on applications. Power limitations mean that commonly used, low-cost passive tags will only operate within a limited reader interrogation zone [1]. Owing to read range limitations in passive RFID, the reader system cost and complexity increases with coverage area size due to the need to deploy more readers. Additionally, interference will arise [2], compromising tag read reliability.

The use of distributed antenna systems (DAS) based on radio over fibre (RoF) for the coverage improvement of wireless communications services has been reported [3], [4], including investigations of the distribution of UHF RFID signals [5]. With RFID over fibre, all readers can be centrally located, far away from the antenna units, reducing maintenance costs, improving security, and the number of readers for a given coverage area can be reduced as one reader can drive multiple antenna units. In addition, taking advantage of the wide bandwidth of optical fibres, the RoF DAS may be shared by different service operators.

In [5], comparable performance between a 30-m length MMF-based RFID and a conventional RFID system was demonstrated, for a single antenna unit, with improved performance obtained for the MMF-based RFID with a triple antenna unit DAS system. The RoF DAS was composed of a commercial Zinwave 2700 hub and its antenna units; a system designed to operate in the frequency range 370 to 2500 MHz [5], and allowing the distribution of multiple wireless communication services. The Zinwave

DAS uses a highly linear 1310-nm DFB laser [6]. In [7], a single-mode fibre-based RoF DAS for simultaneous transmission of UHF RFID, ZigBee and WiFi signals was proposed and demonstrated. However, a slight reduction in the RFID range was reported due to the insertion of the RoF link. As optical source, a 1550-nm DFB laser was used in [7]. Design options for in-building WLAN IEEE 802.11 picocellular systems were analysed in [8], with the experimental work focusing on VCSEL-MMF-based RoF solutions for WLAN signal distribution at 2.4 or 5.5 GHz. Some tests were carried out for an active RFID technology at the 2.4 GHz band. The transmission of UMTS signals at ~2 GHz over a VCSEL-MMF link simultaneously with GSM900, GSM1800, and IEEE 802.11g signals was demonstrated in [9]. In that work, the UMTS performance results showed that the adjacent channel leakage ratio (ACLR) requirements are more difficult to meet when the three other signals are present.

Instead of a multi-service system, if a RoF DAS is needed for RFID signal distribution only, finding a low-cost alternative is imperative. A means of reducing cost of is to replace expensive DFB lasers by vertical-cavity surface-emitting lasers (VCSELs). Another advantage of using VCSELs is their low power consumption.

In this paper, the performance of a passive UHF RFID over low-cost VCSEL-based multimode fibre (MMF) links is reported. We study the system performance for two tag types, and consider spatial diversity techniques. In addition, we compare the conformances of phase-reversal ASK (PR-ASK) and ASK RFID signals with the ETSI spectral mask [10] under nonlinear RoF link conditions. To the best of the authors' knowledge, no previous demonstration has been reported using such a low-cost MMF link. In addition, no similar antenna diversity schemes and/or spectral conformance comparisons have been

previously investigated/carried out for RFID over fibre systems.

2. The RFID over VCSEL-based MMF Link

The downlink of UHF RFID systems for passive tags has high transmit power, up to 2 W ERP (effective radiated power) in the band 865 to 868 MHz [10]. In order to suppress leakage from the high transmit power into the uplink, which may saturate amplifiers and analogue-to-digital converters in the reader's receiver, high isolation is required between downlink and uplink paths. For demonstrated UHF RFID over fibre systems such as [5], the downlink and uplink remote antenna units (RAUs) are in a single module. However, their respective antennas are physically separated by 2 m in order to obtain high isolation.

In this work, a low-cost VCSEL-based RoF link for RFID application has been designed and fabricated with physically separated downlink and uplink RAU modules. High isolation can be achieved with antenna separation of a few centimetres. The designed system is depicted in Fig. 1. The optical modules consist of a central unit (CU) module and separate uplink and downlink RAUs. The CU module enables a single port RFID reader to be connected to it using a circulator to separate the uplink and downlink paths. Commercial off-the-shelf (COTS) 850nm 2.5 Gb/s multimode VCSELs and inexpensive 2.5 Gb/s ROSAs (receiver optical sub-assemblies consisting of PIN photodiode and transimpedance amplifier, TIA) are used in the CU and the RAUs.

In the downlink, the RFID signal is transported from RFID reader via the circulator and CU module to the downlink remote antenna unit. A 20dB RF attenuator is used at the input of the downlink section of the CU to protect the VCSEL from the high RFID reader transmit power levels. A 1.9 V voltage regulator is used to provide 8 mA bias to the VCSEL, which has a threshold current of 1.5 mA, a slope efficiency of 0.11 mW/mA, and a relative intensity noise (RIN) of -130 dB/Hz (at 1 GHz). The VCSEL converts the electrical RFID signal to optical for transport to the downlink RAU via the MMF. A ROSA at the downlink RAU converts the optical signal back to RF and amplifies it. Further amplification is provided after the ROSA by a power amplifier capable of producing up to 2 W RF output. A low pass filter (Minicircuits LFCN-900D+) is used after the power amplifier to suppress unwanted spurious emissions. The filtered RFID signal is wirelessly transmitted and powers the passive RFID tag.

For the uplink operation, the received downlink signal, in addition to powering the passive tag, is modulated with data and back-scattered to the uplink RAU. At the uplink RAU, the received tag signal is converted to an analogue optical signal using a VCSEL. The analogue optical signal is then transported to the uplink section of the CU via MMF. Optical-to-electrical RF conversion is performed using a ROSA at the CU module. The RFID signal exiting the ROSA is further amplified prior to connection to the RFID reader via an isolator and the circulator. The RF isolator suppresses leakage of the downlink signal from the RFID reader into the uplink path. If a RFID reader with separate transmit and receive antenna ports (bistatic ports) is used, the isolator and circulator are not necessary. This may further improve the isolation

between the downlink and uplink, and reduce the overall cost of the system. We note that our VCSEL-based MMF system is simpler and less expensive than that used in [8] as lower bandwidth VCSELs and photodetectors are used and, in the uplink RAU, no preamplifier and AGC circuit are inserted.

As RFID reader, the IDS evaluation board model DK-R902-LP2 (IDS Microchip, Wollerau, Switzerland) is used. It supports the EPC Gen 2 protocol and has a nominal output power of +23 dBm (at 865.7 MHz) and receiver sensitivity of -59 dBm. This reader uses a monostatic configuration in which a single antenna transmits and receives the RFID signal. Using its small, vertically-polarized ceramic patch antenna, the nominal read range is 1 m. For the experiments reported here, the original antenna is replaced by two or three external, circularly-polarized antennas, model Favite FS-GA204. The reader is set to amplitude shift keying (ASK) modulation, Miller 4 coding, and a Type-A reference interval (Tari) of 25 μ s. In contrast with the work reported in [8], we use a passive EPC Gen 2 RFID system, operating at 865.7 MHz, that is environmentally friendly as batteryless tags powered from the reader's transmitted RF signal are used. Active RFID systems are usually much less restricted in range as they use battery powered tags with more complex circuitry.

The experimental results are reported for two tag types. The first tag, the SL900A demo kit from AMS, is based on the SL900A EPC sensor tag chip with a sensitivity of -6.9 dBm (without battery). The second tag is from Smartrack, model DogBone-Impinj Monza R6, with a sensitivity of -20 dBm. In the experiments, both tags were positioned for horizontal polarization. Note that the focus of our experiments involves the achievable read range for the AMS tag. This is because this tag has sensor inputs which can be used in applications such as moisture monitoring [11]. The results for the Smartrack tag are reported mainly for comparison with the results obtained for the AMS tag. It is important to test our RFID over MMF system for two tag cases with different characteristics.

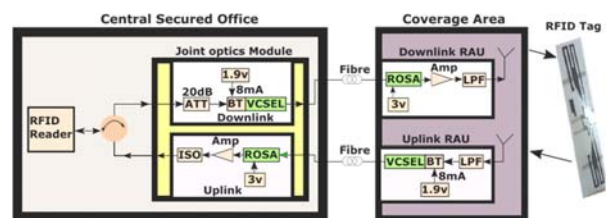


Fig. 1. The RFID over VCSEL-based MMF system. ROSA: photodiode . ISO: RF isolator. LPF: low pass filter. BT: Bias-T.

3. Experimental Results

3.1. The Measured Spectra

As we use low-cost VCSELs in the optical link it is important to verify if there is any distortion to the original RFID signal coming from the MMF link. Thus, the spectrum

of the RFID signal after the MMF link was measured and compared to the spectrum at the reader output. For a fair comparison, the gain of the MMF downlink is set to 0 dB by using RF attenuators. As we can see from Fig. 2, no significant spectral change is introduced by the MMF link.

We also measured the RF frequency response of the 50-m length MMF link, with a practically flat response observed from 800 to 900 MHz (variations within 0.4 dB).

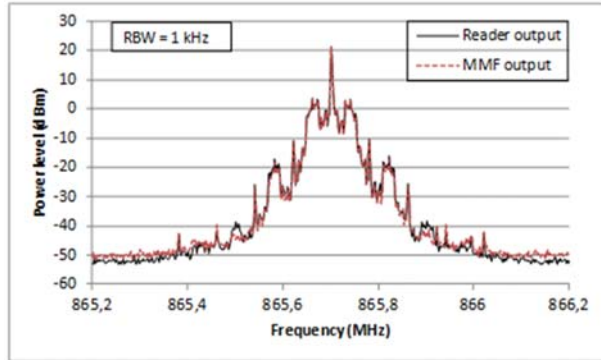


Fig. 2. Spectrum of the RFID signal at the reader output and after the 50-m length MMF link.

3.2. Conventional RFID vs RFID over Fibre System

To evaluate and compare performance for the RFID system with and without the MMF link, the read range and the received power level at the reader are measured. The antenna setup is shown in Fig. 3. For conventional RFID, the antennas are placed about 2 m from the reader. For RFID over fibre, a VCSEL-based 50-m length MMF link is inserted between the reader and antennas. The MMF downlink/uplink gains are set to 0 dB for a fair comparison. The reader's transmitted power (at the Tx antenna input) is 21.2 dBm. To allow the two tag results to be comparable, the measurements were conducted in the same laboratory and with the tags simultaneously interrogated by the reader. For the Smartrack case, as it has better sensitivity, its read range is higher and we had to stop the measurements at 3 m from the transmit antenna to avoid possible strong reflections from a bench and a wall in the laboratory.

The received power levels (measured by the reader) with and without MMF and using the AMS tag are shown in Fig. 4. The -100 dBm power level was not actually measured, it is plotted in Fig. 4 just to represent nulls – those points where no back-scattered signal is detected by the reader. The readings are taken at 20 cm steps, from 20 cm distance up to 80 cm, and in 10 cm steps beyond this. From Fig. 4, it can be seen that the received power for the two cases are very similar for most of the reading points, with the only difference one extra measurable power reading for the conventional RFID case at 120 cm distance.

The read range can be calculated using the Friis free-space formula as [12]

$$r = \frac{\lambda}{4\pi} \sqrt{\frac{G_{tag} G_{Tx} P_{Tx} \tau}{S_{tag}}} \quad (1)$$

where G_{tag} is the tag antenna gain, G_{Tx} is the transmit antenna gain, P_{Tx} is the transmitted power, τ is the power transmission coefficient, S_{tag} is the tag sensitivity. For the AMS tag, G_{tag} is 0.661 dBi (simulated) [13]. The gain of the reader's transmit antenna is 5 dBi. Finally, assuming perfect match between the tag antenna and tag chip ($\tau = 1$), the calculated read range using (1) is 1.3 m for the AMS tag (without battery). This theoretical result is higher than the measured range shown in Fig. 4. The difference might be due to the ideal assumption for the matching parameter τ . For the Smartrack tag, assuming the same antenna gain as for the AMS tag, the calculated read range is 6.1 m.

The power levels obtained with the Smartrack tag are shown in Fig. 5. It can be seen that the received power obtained with the RFID over MMF link is comparable to that of the conventional RFID system for most of the reading points. However, the variability of the received power is more pronounced for the RFID over MMF case. This is most likely due to the increase in the uplink noise caused by the MMF link. This conclusion is corroborated by the obtained results when employing receive diversity (Section 3.3) showing an increase in the uplink SNR and a higher and more stable received power. Within the measurement range of 3 m the Smartrack tag is readable for both RFID with and without MMF, apart from only one null at 180 cm for the RFID over MMF case. The main reason for this null is wireless multipath fading. This unwanted effect is counteracted by employing antenna diversity techniques, as shown in Fig. 8. As the Smartrack tag is moved from 0.2 to 3 m away from the transmit antenna, the received power level shows similar reduction for both cases. It decreases by 18.7 dB and 18.3 dB for the conventional RFID and the RFID over MMF cases, respectively. Due to the significantly better sensitivity of the Smartrack tag (see Section 2), its read range is higher than that of the AMS tag.

The slight reduction in the received power level for the RFID over the low-cost MMF link can be, to some extent, compensated by increasing the MMF link gain. However, any possible increase in the MMF link gain is limited by the acceptable level of transmit power leakage into the reader receiver input (as discussed in Section 2).

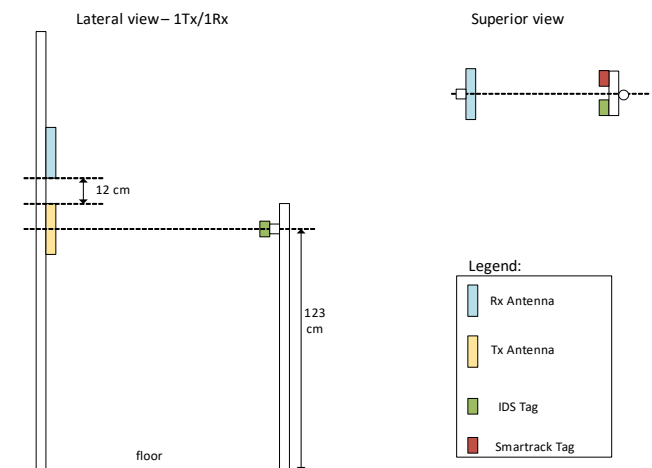


Fig. 3. Antenna setup using 1 Tx and 1 Rx antennas.

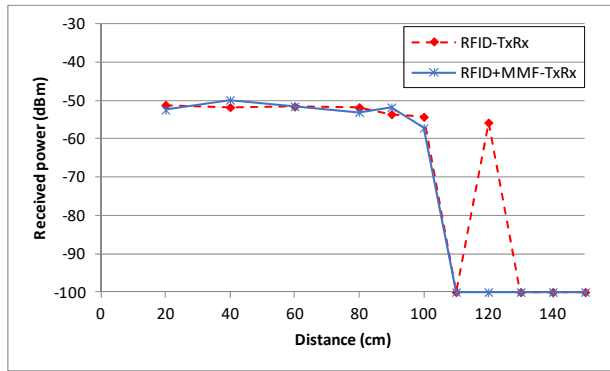


Fig. 4. Received power level as a function of tag distance for RFID with/without 50-m length MMF and AMS tag. The -100 dBm power level just represents nulls (no reading).

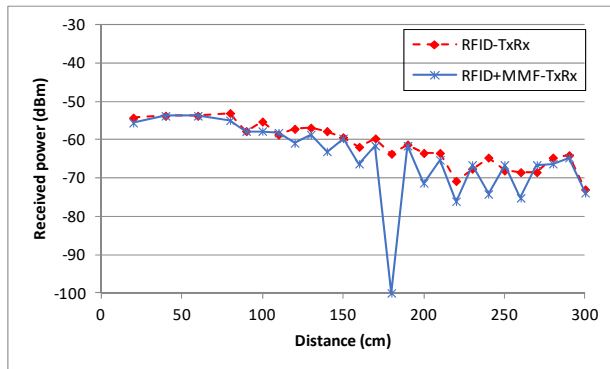


Fig. 5. Received power level as a function of tag distance for the RFID with/without 50-m length MMF and Smartrack tag. The -100 dBm power level represents nulls (no reading).

3.3. Antenna Diversity Experiments

The received power at the RFID reader can be increased and the number of null points reduced without increasing the total transmit power, by using antenna diversity schemes. In this work, the read range and power level of the passive RFID over MMF system is also investigated considering either transmit or receive (spatial) antenna diversity in the vertical direction. The antenna setup for the transmit diversity is depicted in Fig. 6. In this case, the two transmit antennas are connected to the downlink RAU via short RF cables (2.5 meters) and a RF splitter. The transmit power at each antenna input is reduced by 3 dB to give the same total transmit power as for the single antenna case. For the receive diversity experiment, the lower Tx antenna in Fig. 6 was connected as an additional Rx antenna for the uplink RAU.

Our spatial diversity scheme is very different from that reported in [5]. We use a simpler scheme with just one MMF-based RoF link and the spatial diversity is implemented by adding a third antenna to the RAU of our link. In [5], in contrast, the signal level in a room was improved by using a RoF DAS consisting of three RAUs placed in different locations in the room, with each RAU fed by a duplex optical link.

The received power levels obtained with the AMS tag are shown in Fig. 7. With the transmit diversity scheme, the read range of 150 cm is achieved which is 50% higher than that of the single antenna case, although the reader transmit power is the same for both cases. The reason for this higher range is that having more than one reader antenna allows a carrier wave to exist where there would be multipath nulls from a single antenna. The receive diversity improves the received power level at distances near the transmit antenna but the performance is not good at longer distances. This is due to the reduced received RF energy for the AMS tag at longer distances, and the possible destructive interference at the RF combiner inserted before the uplink RAU. In the design of the system, the relative positions of the tag and receive antennas were chosen to minimize the possibility of destructive interference; however, some residual destructive interference may still be present.

In Fig. 8, the power level results for the antenna diversity schemes and the Smartrack tag are shown. We stopped the measurements at 250 cm as no significant difference amongst the three cases was found beyond 230 cm. As shown in Fig. 8, the best performance is obtained with the receive diversity scheme. For example, at the tag-reader distance of 2.2 m, the received power level for the receive antenna diversity scheme is higher than that for the single antenna case by around 13 dB. Also of importance is that the variability of the received power level is significantly reduced for the receive antenna diversity case. The impact of the transmit diversity on the system performance is less significant for the Smartrack tag compared to the AMS tag. This is due to the fact that the Smartrack tag needs much less energy to be powered on than the AMS tag.

3.4. Performance Results for a 300-m MMF Link

The experiment was repeated with the same electro-optic modules but with 300-m length 50/125 μm (downlink) and 62.5/125 μm (uplink) MMF. The antenna setup with 1 Tx and 1 Rx antennas is used, as depicted in Fig. 3.

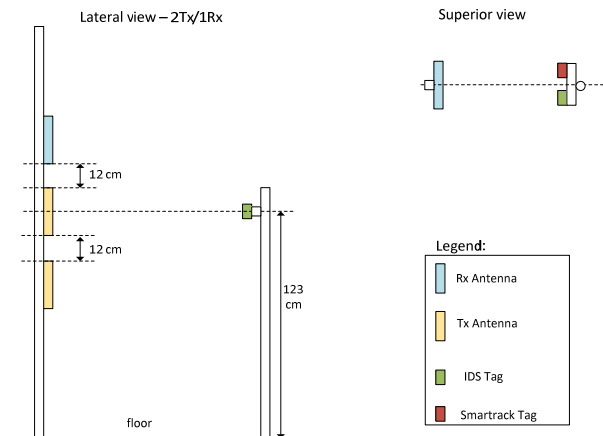


Fig. 6. Antenna setup for the transmit diversity experiments

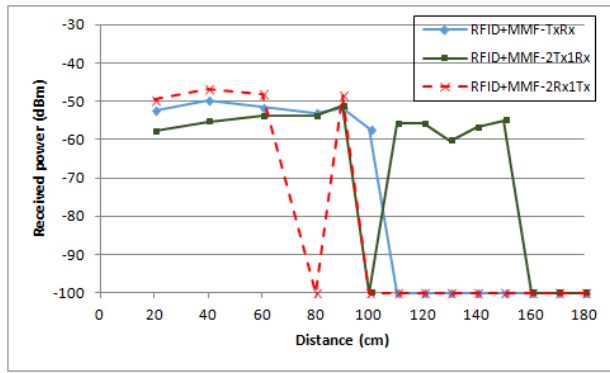


Fig. 7. Received power level as a function of tag distance for the RFID over 50-m length MMF and AMS tag. Single antenna (Tx/Rx), transmit antenna diversity (2Tx/1Rx), and receive antenna diversity (2Rx/1Tx) schemes. The -100 dBm power level just represents nulls (no reading).

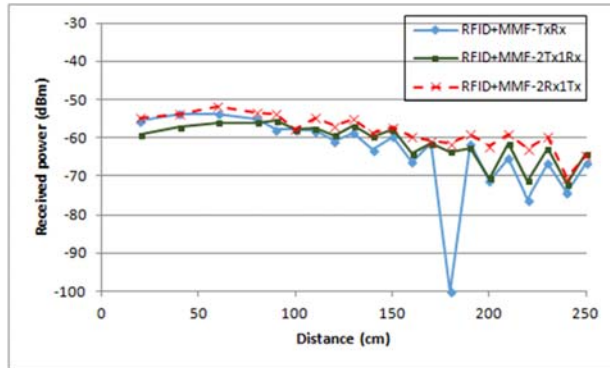


Fig. 8. Received power level as a function of tag distance for the RFID over 50-m length MMF and Smartrack tag. Single antenna (Tx/Rx), transmit antenna diversity (2Tx/1Rx), and receive antenna diversity (2Rx/1Tx) schemes. The -100 dBm power level just represents nulls (no reading).

The output power (at the RAU) of the 300-m MMF set-up was set to the same level as for the 50-m MMF one, by increasing the input power to the CU. Similar read ranges can be maintained as the increased input power compensates for the increased link attenuation. However, this means that the RoF link is now operating in the nonlinear regime.

From Fig. 9, it can be seen that a read range of 2 m is achieved, higher than that achieved by the 50-m link. In Section 4, a distortion analysis shows that this improvement can be attributed to the AMS tag being able to harvest more energy, resulting from the higher power level of the harmonic and intermodulation distortion frequencies. We note that the read range of the AMS tag used is very dependent on the level of power converted from the received electromagnetic waves. A short-power on test was carried out with a battery (without MMF link), confirming that the achievable read range was around 3 m. An additional reason for the better read range obtained with the 300-m link case is that the higher power level of the harmonic frequencies

actually creates a type of “frequency diversity” scheme as those frequencies are carrying the same modulated information. Some commercial tags can even backscatter a RFID signal at the third harmonic and the exploitation of this effect for establishing frequency diversity in RFID systems was proposed in [14].

This result shows that the developed low-cost VCSEL-based MMF system can work for RFID UHF applications up to (at least) 300-m fibre length. It also shows that the RFID reader can detect tags even if the RoF link is operating nonlinearly. Thus, RFID systems can make use of pre-installed fibre of different lengths and attenuation with flexibility in power budgeting for maximum read range. Low-cost and low-power consumption components such as VCSELs can be used, leveraging at least some of the distortion to maintain (or improve) read range. There may be limits imposed by regional RFID regulations and further investigation is needed to consider nonlinear transmission systems (RF or RoF) and RFID applications.

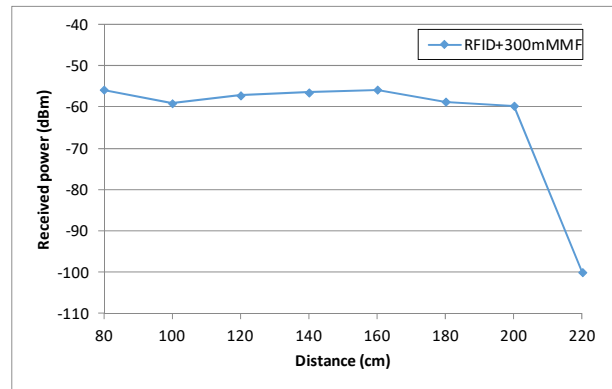


Fig. 9. Received power level as a function of tag distance for the RFID over 300-m length MMF, AMS tag, and single antenna (Tx/Rx) setup.

4. Simulation Studies of RFID under RoF Nonlinearity

In this Section, we report simulation results of the RFID spectrum after the VCSEL-based 50-m length MMF link. Either ASK or phase-reversal ASK (PR-ASK) RFID signals, measured from the reader output, are used as input for the simulations. The nonlinear behaviour of the MMF link was characterized by using a single-tone measurement approach [15] set at the RF frequency of 865.7 MHz. With this approach, the input RF power is varied and the output power measured using a sinusoid with constant frequency. Then, the measured data is fit to a model formulation. In this work, the extracted nonlinear model is used to investigate the increase in the RFID signal distortion with increasing MMF link power drive level. The reported results are for the input power levels (at CU input) of -5.6, -0.6, 1.9 and 4.4 dBm (the 1-dB compression point of the MMF link). The input/output spectra are scaled so as to comply with the ETSI spectral mask [10]. The adjacent channel power ratio (ACPR) is used as metric of spectral distortion. In addition, the necessary back-off in the output power due to the

increase in signal distortion and for ETSI spectral mask compliance is discussed.

In this work, the nonlinear amplitude characteristic of the MMF link is modelled by the following rational function

$$y(x) = \frac{p_1x^5 + p_2x^4 + p_3x^3 + p_4x^2 + p_5x + p_6}{x^4 + q_1x^3 + q_2x^2 + q_3x + q_4} \quad (2)$$

where x is the input signal, y is the MMF output signal, p and q are the model coefficients (listed in Table 1). The rational function of (2) was chosen due to the excellent fit to the measured data.

In Fig. 10, the spectra of the ASK RFID signal at the reader output and after the 50-m length MMF link for the input power level of -5.6 dBm are shown. This drive level is 10 dB below the 1-dB compression point of the MMF link and represents a linear link case. From Fig. 10, it can be seen that the MMF output spectrum generated by using the rational model of (2) can reproduce very well the reader output spectrum. The power level of the RF carrier at the MMF output is +17.9 dBm, which means a back-off of 15.1 dB from the ETSI limit of 33 dBm ERP. Note that, by filtering just the small peaks near +/- 400kHz, the average power level could be increased by around 4 dB.

The increase in spectral distortion when the drive level of the 50-m length MMF link is increased can clearly be seen from Fig. 11. The drive level is -0.6 dBm (5 dB below the 1-dB compression point). To conform to the ETSI spectral mask the power level of the RF carrier at the MMF output is now backed-off by 16.7 dB. Thus, by an additional back-off of 1.6 dB in relation to that of the MMF linear case the link can be set to operate 5 dB closer to its 1-dB compression point.

The main band and side lobe powers, and the ACPR results are presented in Table 2, for the ASK modulation. The frequency ranges for average power calculations are: -100 to +100 kHz (main band), -300 to -100 kHz (low adjacent band), and 100 to 300 kHz (high adjacent band). The side lobe power is calculated for a 10-kHz bandwidth, from 30 to 40 kHz. To maintain the spectral mask compliance, the main band and the side lobe powers need to be reduced by 6.3 and 7.9 dB, respectively, when the input power increases from -5.6 to 4.4 dBm, as shown in Table 2. Both the low and high ACPR reduce by 5 dB when the input power increases up to 4.4 dBm.

The spectral results considering the PR-ASK modulation, for the MMF input power level of -0.6 dBm are shown in Fig. 12. In this case, the power level of the RF carrier at the MMF output is backed-off by 17.5 dB for ETSI spectral mask compliance, which is higher than that for the ASK RFID case. However, by comparing the levels of the first side lobes in Figs. 11 and 12, we can see that the level of the PR-ASK modulated signal is significantly higher than that of the ASK modulated one.

Table 1 Nonlinear model coefficients of the 50-m length MMF link

$p_1 = 0.0787$	$q_1 = -0.4783$
$p_2 = 0.7364$	$q_2 = 0.1383$
$p_3 = -0.1461$	$q_3 = -0.0358$
$p_4 = -0.0542$	$q_4 = 0.0048$
$p_5 = 0.0139$	
$p_6 = 2.5118e-08$	

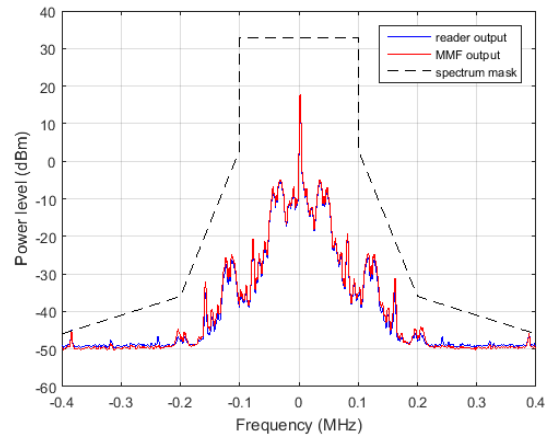


Fig.10. Spectra of the ASK RFID signal at the reader output (input signal) and after the 50-m length MMF link. Power level (at CU input) = -5.6 dBm (10 dB below the 1-dB compression point).

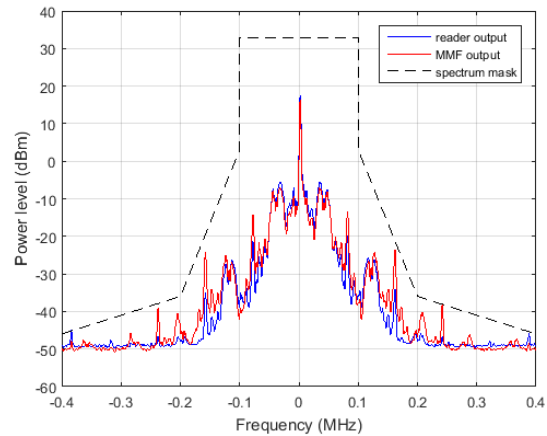


Fig. 11. Spectra of the ASK RFID signal at the reader output (input signal) and after the 50-m length MMF link. Power level (at CU input) = -0.6 dBm (5 dB below the 1-dB compression point).

Table 2 ASK RFID-RoF average power and ACPR results

Input power (dBm)	Main band power (dBm)	Side lobe power (dBm)	Low ACPR (dBc)	High ACPR (dBc)
-5.6	18.5	+0.5	-48.0	-48.0
-0.6	16.8	-1.6	-46.8	-46.9
+1.9	11.6	-7.4	-45.1	-45.1
+4.4	12.2	-7.4	-43.0	-43.0

Table 3 PR-ASK RFID-RoF average power and ACPR results

Input power (dBm)	Main band power (dBm)	Side lobe power (dBm)	Low ACPR (dBc)	High ACPR (dBc)
-5.6	19.0	8.8	-48.3	-48.2
-0.6	18.2	8.3	-47.3	-47.3
+1.9	10.7	0.9	-45.5	-45.6
+4.4	8.5	-1.3	-43.5	-43.6

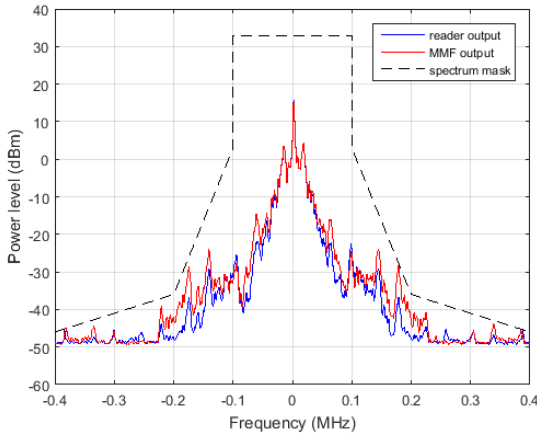


Fig. 12. Spectra of the PR-ASK RFID signal at the reader output (input signal) and after the 50-m length MMF link. Power level (at CU input) = -0.6 dBm (5 dB below the 1-dB compression point)

In Table 3, the main band and side lobe powers, and the ACPR results are listed, for the PR-ASK RFID. For the average power calculations, the same main/adjacent frequency ranges are used as those for the ASK RFID case. The side lobe power in Table 3 is calculated for 10-kHz bandwidth, but now ranging from 15 to 25 kHz. The main band and the side lobe powers are reduced by 10.5 and 10.1 dB, respectively, when the input power increases from -5.6 to 4.4 dBm. The low and high ACPR reduce by 4.8 and 4.6 dB, respectively, when the input power increases from -5.6 to 4.4 dBm. Importantly, the average power of the PR-ASK modulated signal is 9.9 dB higher than that of the ASK modulated one, for the -0.6-dBm input power case.

The PR-ASK has better spectral efficiency in comparison with the ASK modulation. In this work, the PR-ASK modulated information is carried in the side lobe located around 20 kHz (see Fig. 12) while the modulated signal is located around 40 kHz for the ASK RFID case (see Fig. 11). Thus, for nonlinearly operating RF/RoF systems, the lower bandwidth of the PR-ASK RFID makes it easier to apply filtering to reduce the level of distortion products in comparison with the ASK RFID.

For real applications the MMF link is usually set well below its 1-dB compression point. For low link nonlinearity, e.g. 5 dB below the 1-dB compression, the simulation results show that less reduction in the main band power is needed and significantly higher level of signal modulation power can be achieved for the PR-ASK RFID case in comparison with ASK RFID.

5. Conclusion

In this work, a low-cost VCSEL-based MMF link has been proposed and demonstrated for passive UHF RFID applications. Considering that many optical sources are needed in a RoF DAS system, the advantages of using VCSELs instead of DFBs are two-fold: reduced deployment cost and low power consumption. Experimental results show that it is possible to obtain almost the same performance over a VCSEL-based MMF link in comparison with a conventional RFID system. The results also show that the performance of the RFID over MMF system can be further improved by using spatial antenna diversity without increasing the total transmit power level. Simulation studies of RFID over fibre with RoF nonlinearity show that PR-ASK RFID allows for higher levels of RF carrier and modulated signal power than the ASK RFID, for low levels of nonlinearity.

As future work, the VCSEL-based MMF links can be tested in broader system scenarios comprising multiple RAUs and multiplexed transmissions, which should further increase the RFID system performance. We can also consider other antenna setups and diversity schemes. Additionally, digital signal processing techniques (e.g. predistortion, PAPR reduction) can be used in the RFID reader to compensate for system nonlinearity. Moreover, digital spectrum shaping filters can be used to aid with spectral mask adherence while maximizing power spectral density in regions of the spectrum where local spectral mask specifications allow it.

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