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Miniaturization (0.2 g) and evaluation of attachment techniques of telemetry transmitters

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Summary

We have developed a miniaturized very high frequency (VHF) transmitter design for radio-tagging small animals. The average mass of the circuitry is 0.084 g (range 0.081–0.087), hence, with the smallest power cell, complete tags weigh 0.2 g and have a life of 18–22 days. We further demonstrate that with such small tags the technique of attaching the device to the animal's body strongly affects the effective radiated power, and thus transmission ranges. Ideally the attachment couples the electronics to the animal's body as a ground plane for improved radiation. The transmitter allows the application of radio-tracking to be expanded to new taxa whose spatial behaviour and population dynamics are largely unknown, for example arthropods, reptiles or amphibians. The new design is also suitable for miniature implants and signal modulation with sensors.

Key words: radio-telemetry, circuit design, transmitter attachment, field technique.

Introduction

Radio-telemetry is a key approach to analysing how animals use space and time in response to environmental factors, and for recording physiological data in the laboratory and from free-living animals. The technique was developed shortly after the invention of semiconductor amplifiers (Barr, 1954), and the first field studies on wild animals were reported in the early 1960s (e.g. LeMunyan et al., 1959; Cochran and Lord, 1963). Today, a number of manufacturers offer equipment for various purposes and detection ranges, ranging from ARGOS PTTs to implantable devices transmitting data on several channels (for an overview, see Kenward, 2001). However, since radio-tagging should in no way affect an animal's health or behaviour, the application to very small animals is still a technical challenge. Although many papers report no adverse effects (e.g. Brigham, 1989; Hill and Talent, 1990; Neudorf and Pitcher, 1997; Naef-Daenzer et al., 2001), others found effects, for example, on activity time allocation (Hooge, 1991), foraging performance (Massey et al., 1988; Ackermann et al., 2004) and survival (Petty et al., 2004). Therefore, both minimizing the volume and mass of radio-tags and optimising attachment techniques are essential. Due to the steady development of electronics components and assembling techniques, the mass of the circuitry of a simple 'beeper' radio-tag has decreased to ~0.25 g (without battery). Nevertheless, technical limitations still constrain the use of the technique, often to an unacceptable extent. For example, telemetry applications on arthropods are restricted to the largest species (Janowski-Bell and Horner, 1999; Sword et al., 2005). Amongst the subjects that are too small to carry radio-tags are species of global economic importance or of conservation concern, and excellent example organisms for behavioural ecology, evolutionary biology or physiology/endocrinology. For many purposes, alternative techniques are lacking. For example, harmonic radar transponders (Riley and Smith, 2002; Cant et al., 2005) can be built extremely small but have serious disadvantages. First, all tags operate on one frequency, which prevents the remote identification of individuals. Second, the microwave signal is strongly suppressed by vegetation, which greatly restricts the application of the technique. Thus, the usable ranges are short (<50 m with a hand-held transmitter/receiver, <1 km in open area with vehicle-mounted equipment). Passive integrated transponders (PIT tags) are also very small and allow for individual identification. However, their detection ranges are far too short (<1 m) to allow the range use of animals to be recorded. Furthermore, neither of the two techniques allows for the transmission of behavioural or physiological data. Therefore, further miniaturization of VHF radio-transmitters fills a crucial gap, since it offers both individual identification and data telemetry over considerable distances with portable and relatively inexpensive equipment.

To study the range use and survival of juvenile barn swallows *Hirundo rustica* L. after fledging, we improved both range and life of miniaturized transmitters. We present construction details and technical data for a new ultra-miniature VHF transmitter. Specifically, we address two main issues of miniaturization. (1) We propose a design for the transmitter's circuitry that maximizes the output while keeping the number of components small and the average current drain low. In particular, the pulse-forming circuit and antenna-matching circuit offered potential for development. (2) We analyse the radiated power of the newly developed transmitter. With tags that are very small relative to the radiated wavelength, factors such as the size (mass) of the battery, and the technique of attaching the transmitter become increasingly important. So far, these effects have not been quantified.

Materials and methods

Technical approach

Circuit design

The basic design of radio frequency oscillators for telemetry changed little in the last decades (Cederlund, 1979; Cheeseman and Mitson, 1982; Kenward, 1987). A major drawback of the simple self-pulsing designs was that controlling the oscillator with very simple resistor–capacitor (RC) pulsers restricted the setting of pulse interval and pulse width. Therefore, very low duty cycles (that is, short pulses at long pulse intervals) were difficult to realize. Consequently, RC-pulsed designs draw some 50–100 μA (Kenward, 1987; Naef-Daenzer, 1993). By contrast, transmitters that are controlled by a transistor-controlled multivibrator or a microprocessor consume much less power (20–40 μA), although at the cost of considerably increased volume and mass of the circuitry.

We used the P-Spice® software (Cadence Design Systems Inc., San Jose, USA) to evaluate a variety of one- and two-stage circuits with respect to the ratio of radiated power to the number of electronic components. Since adjustable components for oscillators (capacitors, inductors) are large compared to standard components, a main aim of the evaluation was that the circuits should oscillate reliably without any tuning elements. Based on the modelling results, different spatial layouts were realized and tested in the laboratory and in the field.

Transmitter construction

All circuits were realized on a 100 μm double-side printed circuit board. To allow modifications of pulse length and interval by exchanging components, the timer capacitor and resistor were arranged at the periphery of the board. All capacitors and resistors were of 0402 size (1.0 mm×0.5 mm, height 0.2–0.5 mm). We used laser-cut inductors of 0402 dimensions, except for the large inductor L2, which was available as a wire-wound type of 0603 size (1.5 mm×1.0 mm×1.0 mm). We used two types of crystals differing in dimensions and mass, and also in the resulting radiated power. Details of all electronic components and manufacturers are given in Table 1. For the antenna we used either 13 cm of a 0.15 mm multistrand steel cord originally used for fishing, or 7 cm of 0.03 mm steel wire (unwound from the multistrand cord).

Measurements of transmitter performance

Absolute measurements of the effective radiated power (ERP) are difficult and require extensive infrastructure and equipment. To validate the performance of the transmitter we used a simple comparative approach that allows only rough absolute estimates of ERP but accurate comparison of different layouts, including a control group of 16 commercially available miniature transmitters (Holohil Inc., Carp, Ontario, Canada). We used a HAMEG 5012 Spectrum Analyser (Mainhausen, Germany) for measuring the power radiated at the nominal frequency in the 148 MHz band and at harmonics in the range of 50–600 MHz. The antenna of the transmitters was inserted into a piece of tubing attached to the

Table 1. *Components list and specifications for the miniature transmitter*

Component	Value/Type	Size	Manufacturer
R1	1.8–2.7 MΩ	0402 (1.0 mm×0.5 mm×0.2 mm)	
R2	15–18 kΩ	0402	
R3	0–100 Ω	0402	
C1	0.47–1.0 μF	2×0402	SRT Technologies, Cadolzburg, Germany
C2	220 nF	0402	
C3	15 pF	0402	
C4	3.3 pF	0402	
C5	2.2 pF	0402	
L1	100 nH	0402	Stelco, Newmarkt, Germany
L2	1.0 μH	0603 (1.5 mm×1.0 mm×1.0 mm)	Stelco
L3	100 nH	0402	Stelco
T1	BFR92	SOT323 (2.0 mm×1.25 mm×0.9 mm)	Philips, Zurich, Switzerland
	S852TF	SOT490 (1.7 mm×0.9 mm×0.8 mm)	Vishay, Selb, Germany
Q	Large	(5.0 mm×3.2 mm×1.1 mm)	Micro-crystal, Grenchen, Switzerland
	Small	(3.5 mm×2.2 mm×0.7 mm)	TeleTec, Saitama, Japan
PDTA114	PNP, 10 K bias resistor	SOT490 (1.7 mm×0.9 mm×0.8 mm)	Philips

For widely available components, no particular manufacturer is indicated.
Components are identified in Fig. 1.

antenna of the instrument and positioned such that the transmitter was at least 20 cm away from any metallic parts. Measurements were taken of the bare transmitter and with the transmitter attached to a dummy body of 12 g. This dummy animal was made from a finger of a laboratory glove filled with 0.9% NaCl solution. Two attached nylon sticks (1.5 cm), simulating legs, allowed transmitters to be mounted using the same leg-loop harnesses as with real birds (Rappole and Tipton, 1991). The effect of this dummy on transmitter performance did not differ from that measured with a dead small bird (*N*=1 transmitter). Measurements of the current drain were taken while running the transmitter on a precision power supply at 1.55 V (equivalent to silver-oxide cells) or 3.2 V (lithium-cells) using a Tektronix 1002 oscilloscope (Bracknell, UK).

Results

Transmitter circuit

P-Spice® simulations revealed that a simple two-stage design (i.e. an oscillator circuit and a coupled amplifier/multiplier stage, e.g. the design suggested by Kenward, 1987) is very difficult to realize with a minimum number of components. Although all simulations predicted considerable radio frequency (RF) power of up to –17 dBm at 1.55 V for the oscillator stage, a model circuit further improving the radiated power with very simple amplifier stages could not be found. In particular, the tuning of the amplifier stage was so sensitive that the simulation results offered little prospect to realize such designs without accurate tuning. Giving priority to minimum mass and volume of the electronics, we therefore abandoned the evaluation of two-stage designs. The favoured circuit diagram is given in Fig. 1.

A marked reduction of the average current drawn was obtained with a modified pulse-forming circuit. Astable multivibrators require 6–8 parts and thus would add considerable volume and mass even if twin transistors and smallest capacitors and resistors were used. Here we propose a new solution to the problem of controlling beeper transmitters with a multivibrator consisting of only three components. We improved the RC pulser by inserting a PNP transistor between the 'timer' capacitor C1 and the base of the RF transistor. This transistor cuts the pulse width to about half the duration obtained with the common RC pulser while keeping the pulse interval constant. Using the smallest components (T1: SOT490, C1: 2×0402, R1: 0402), this multivibrator has a volume of 3 µl and a mass of ~10 mg.

Transmitter mass

For field use the circuitry was coated with two layers of acrylic varnish (Tropicalising varnish, Electrolube®, Wentworth Inc., Berkshire, UK). The average mass of the finished transmitters was 0.084 g (range 0.081–0.087 g, *N*=5) with the small crystal and 0.135 g (range 0.125–0.140 g, *N*=17) with the larger crystal. Both versions are considerably smaller than any commercially available transmitter. A comparison of dimensions and mass with the smallest commercial types is given in Table 2, and a photograph of the assembled circuitry is given in Fig. 1.

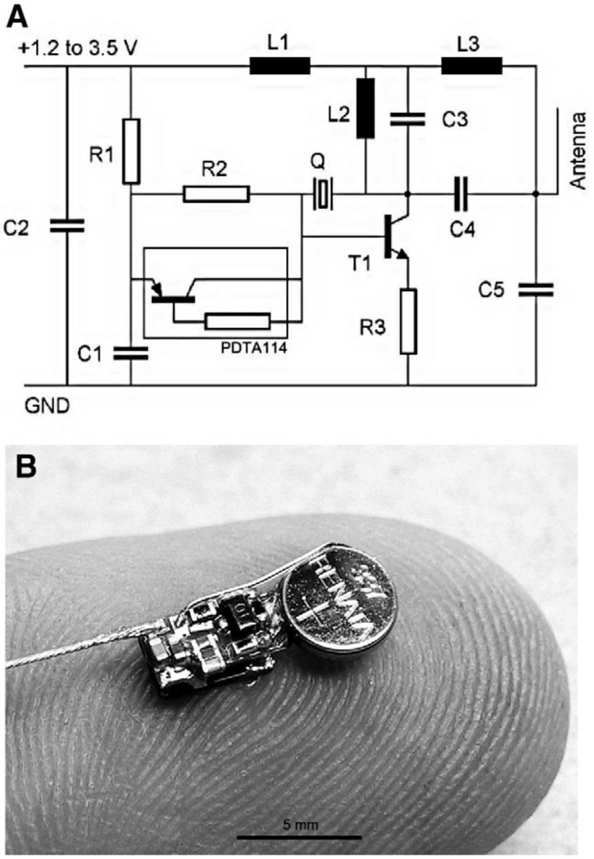

Fig. 1. (A) The circuit diagram and (B) a photograph of the miniature transmitter on a human finger. The list of components and specifications are given in Table 1. Scale bar, 5 mm.

Performance and power consumption

With the values for the multivibrator set as in Table 1, the transmitter radiated pulses of 10–20 ms at intervals of 800–1500 ms. The average current drawn depended on the values of R1 and C1 and ranged from 15 to 35 µA (Table 3). This is similar to multivibrator or CMOS controlled transmitters, but at a much lower volume and mass of the circuitry. Using the S852 transistor the average current drawn could even be reduced to 8–9 µA (at a 0.01 duty cycle). Therefore, the expected life of the 0.2 g tag (with a 337 size cell, 8 mA h) is 22 days for the 15 µA version and up to 35 days in the 9 µA version.

The pulse width was linearly correlated with the capacity of C1, independently of the resistance of R1. A 100 nF increase in C1 resulted in a 2 ms increase in pulse width (Table 3).

At a given value of C1, the pulse interval was linearly correlated with R1. However, the slope of the regression varied in relation to C1. The detailed regression coefficients and

Table 2. *Dimensions of the miniature transmitter compared to the smallest types offered by commercial manufacturers*

Type	Length (mm)	Width (mm)	Height (mm)	Volume (μl)	Mass (g) (range)	Data source
Large Q	5.4	3.4	2.9	53.2	0.135 (0.125–0.140)	
Small Q	5.2	3.1	2.3	37.1	0.084 (0.081–0.087)	
Holohil	7.0	4.6	4.0	128.8	0.240	F. Anderka, personal communication (www.holohil.com)
Titley	7.0	5.0	2.5	87.5	0.220	www.titley.com.au
Biotrack	8.0	5.0	4.0	160.0	0.210	W. Cresswell, personal communication (www.biotrack.com)

Size and mass are given for the ready-to-use transmitter without battery.

Table 3. *The pulse width and pulse interval of the miniature transmitter in relation to the settings of the multivibrator*

		Coefficient		
Parameter	Intercept	R1 (MΩ)	C1 (nF)	Multiple statistics
Pulse width (ms)	3.25±0.63	NS	0.020±0.0006	$F_{2,13}$=499.2, $P<0.001$, r^2_{adj}=0.99
Pulse interval (ms)	1098.99±149.76	680.07±51.11	1.54±0.16	$F_{2,13}$=139.49, $P<0.001$ r^2_{adj}=0.95

R, resistor; C, capacitor (see Fig. 1).
Values are means ± S.E.M., *N*=17 transmitters.
NS, not significant.
Power consumption per pulse (μAs)=5.2+0.033C1; average current drain (μA)=40.35–62.08(logR1).

statistics are given in Table 3. The circuit oscillated reliably with values of R1 of 1.0–2.7 MΩ, allowing duty cycles of down to 0.008 to be set (i.e. one 16 ms pulse per 2 s). Lower duty cycles are undesirable from the point of view of detectability of the signal in the field.

Radiated power

The radiated power of the bare transmitters varied considerably in relation to the type of crystal, antenna length and battery type. In the configuration with the larger crystal, a 396 battery (transmitter mass 0.6 g) and a 13 cm antenna, the average ERP was –15.8±2.0 dBm (mean ± S.D., *N*=7), which is slightly better than the –17 dBm predicted by the P-Spice simulation. The ERP of the new design was equivalent to the average ERP of the control group of commercial types (–15.9±3.7 dBm, *N*=16; measurements taken with transmitters attached to the dummy body). The parts of the circuit (L3, C4, C5) that match the antenna to the oscillator strongly improved the radiation at the nominal frequency of 148.5 MHz. Fig. 2 shows the frequency spectrum of the new design compared to that of the circuit lacking L3, C4 and C5 (i.e. the design of Cochran, 1963). The output at the nominal frequency was improved whereas radiation at frequencies above 180 MHz was strongly suppressed. Thus, the π-filter-like matching circuit yielded a higher gain at the nominal frequency than any transistor amplifier stage.

Also measured on the dummy body, the average power of the smallest (0.2 g) configuration was –21.6±2.6 dBm (mean ± S.D., *N*=5). The reduction in ERP compared to the larger type was mainly due to the short antenna and to the smaller dimensions (see below).

We observed a strong non-linear increase of the radiated power with the mass of the battery attached to the transmitter ($y=-1.34+19.33x^{0.538}$, $r^2=0.83$, $P<0.001$; Fig. 3). By contrast, the current drain during pulses was constant over all

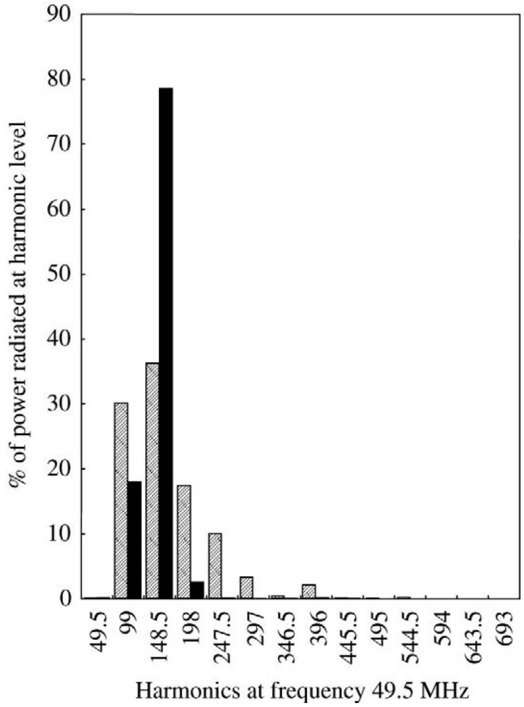

Fig. 2. The radiated spectrum of the miniature transmitter at harmonics of the crystal frequency of 49.5 MHz compared to the spectrum with unmatched antenna (i.e. omitting L3, C4 and C5 in Fig. 1). With the matching circuit the largest proportion of radiated power is emitted at the nominal frequency of 148.5 MHz.

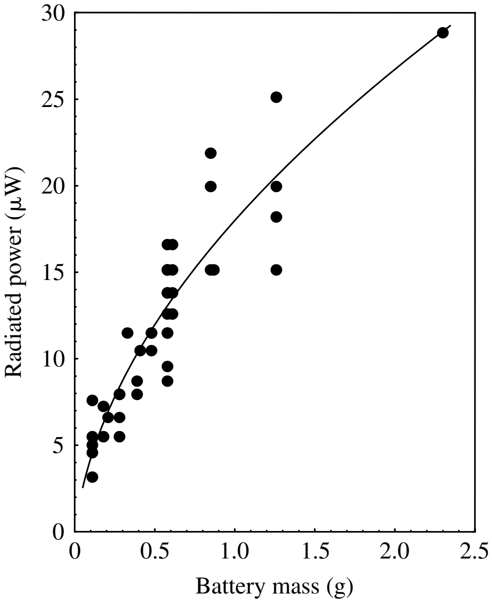

Fig. 3. The radiated power of the miniature transmitter (larger crystal, 13 cm antenna) relative to the mass of attached silver-oxide cells. There is a marked increase from 4.8 µW with the smallest 337 cells (0.12 g) to c. 29 µW on a 076 battery (2.3 g). Fit: $y=-1.343+19.331x^{0.538}$, $r^2_{\text{adj}}=0.82$, $N=43$.

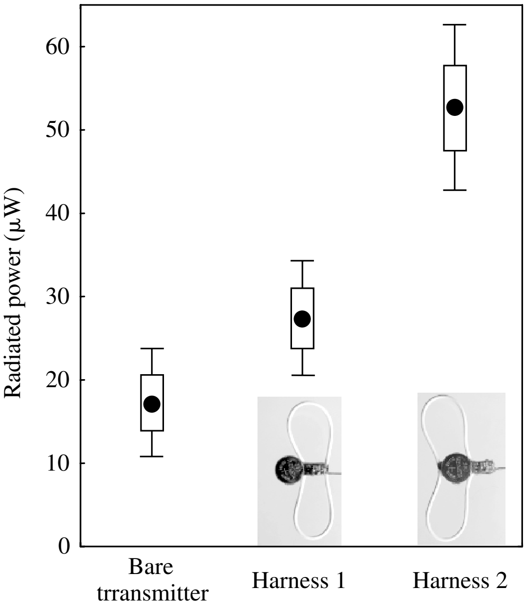

Fig. 4. The radiated power of the miniature transmitter as measured in different configurations (circles = mean, boxes = S.E.M., whiskers = S.D.). When attached to a dummy body of 12 g, the effective radiated power of the transmitters improved. If the harness was attached to the transmitter (harness 1) the gain in ERP was significantly smaller compared to the version with the harness attached to the battery. (harness 2; paired samples $t_6=7.88$, $P<0.001$).

dimensions of cells (average 1.81 mA at 1.55 V; min. 1.78 mA, max 1.84 mA). This indicates that the effect was not due to insufficient cell capacity but was caused by the increasing lack of ground plane area with decreasing cell size. According to this correlation, the transmitter's ERP was 4.8 µW with the smallest 337 cell (0.12 g) and 28.9 µW on a 2.3 g 390 battery, respectively. This indicates considerable physical constraints in maximizing the output while minimizing the total transmitter mass and volume.

Attaching the transmitter to a body generally improves the ERP compared to the transmitter running in free air. We found that this effect becomes very important with extremely miniaturized designs, since different attachment techniques caused a substantial effect on the ERP (Fig. 4). If a Rappole-type harness (Rappole and Tipton, 1991) was attached to the circuitry, the mounted transmitters radiated on average 27.43±9.83 µW (mean ± S.D.) compared to 17.36±8.77 µW for the un-mounted transmitters (paired samples $t_6=1.84$, $P=0.12$, dependent samples tests performed on a sub-sample of 7 transmitters measured in each of the configurations). However, if the harness was attached to the battery of the transmitter, the ERP was 52.72±13.99 µW, a significant improvement compared to both the free running transmitter (paired samples $t_6=5.53$, $P=0.002$) and the version with the harness attached to the transmitter (paired samples $t_6=7.88$, $P<0.001$). This signifies that in extremely miniaturized designs the technique of attaching the transmitter to the animals has a strong effect on the ERP and thus, the operational range of the transmitters. The effect was probably due to a capacitive coupling to the animal's body.

Discussion

As the overhelming proportion of animal species are small (<20 g), the new transmitter design greatly expands the range of radio-telemetry applications. The 0.2 g tag can be attached, for example, to a 4 g bird or mammal (transmitter ⩽5% of body mass) or to a 2 g insect (transmitter ⩽10% of body mass; Cant et al., 2005). The reduction in mass and volume allows telemetry applications to be expanded to new taxa such as large butterflies and other arthropods, plant seeds, amphibians, reptiles and fish.

Furthermore, the design significantly improves the ratio of ERP to the average current drawn and to tag mass and volume. In particular with radio-tags of 0.5–2.0 g, this yields a substantial gain in tag life per unit mass. For example, the new design in a 1.0 g configuration (i.e. with 392 cell, 18 µA) would run for 105 days, whereas commercial types have an expected life of about 60 days (e.g. ATS 2420: 55 days, www.atstrack.com). In free air (i.e. transmitter and antenna >2 wavelengths above ground) the radiated power of the 0.2 g tag gives an operational range of c. 2 km (at –135 dBm receiver input). Although this range was confirmed in field tests, we have not yet collected experience with tagged animals. Ground-to-ground ranges are hardly predictable because the signal strength depends greatly on the positions of transmitter and antenna, and may vary from 50–500 m.

Although the transmitter was primarily designed for tracking animals in the field, the circuit can be modified for many more research purposes. For example, very small implants could be constructed by using a short coiled or loop antenna. Furthermore, the circuit can be modified to transmit physiological or behavioural data by adding sensory devices.

Research implications

There is experience with radio-tagging small animals down to ~10 g (Naef-Daenzer et al., 2001; Bontadina et al., 2002), confirming the 5% rule for the acceptable transmitter load, at least for birds and bats. The new transmitter will allow the application of radio-telemetry to be expanded on taxa for which virtually no experience exists, for example insects and other invertebrates, and small amphibians. Pilot studies with smaller species have revealed that animals carrying very large and heavy loads (stag beetle *Lucanus cervus* L, up to 30% of body mass; Sprecher-Uebersax and Durrer, 2001; Riecken and Raths, 1996) did not behave like untagged animals.

It is difficult to draw general conclusions on maximum acceptable loads or attachment techniques, since radio-tagging probably affects different species differently. In addition to tag mass, the volume of the package is also an important issue if small animals are to be tagged. Therefore, researchers should carefully evaluate and eliminate transmitter effects. Minimizing the impact on study animals should be preferred over maximization of technical reliability.

List of abbreviations

C	capacitor
CMOS	complementary metal oxide semiconductor
ERP	effective radiated power
PIT	passive integrated transponder
R	resistor
RC	resistor–capacitor
RF	radio frequency
VHF	very high frequency

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