Wireless Without Batteries: Extraordinarily Low-Powered Microwave Communications

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Abstract: Recent advances in communications, electronics, and RF energy-harvesting indicate that extraordinarily long separation distances (100m or more) between readers and passive microwave transponder-sensors are possible – even for readers that obey low-power, unlicensed spectrum regulations.

Backscatter communication is a remarkably low-powered method for exchanging radio information. Its most common use today is in the field of radio frequency identification (RFID), where a transceiver unit (i.e. reader) retrieves identification information from an RF transponder tag that backscatters a waveform as it adds modulated data. This technique requires so little power at the RF tag that it is often possible to run the tag electronics off of energy harvested from the impinging RF waveform [Dev05, Dob07]. Recent advances in energy-harvesting microwave communications will enable extraordinarily long ranges – and new applications – for passive transponders [Dur10]. These following techniques provide significant gains for these passive systems.

Power Optimized Waveforms (POW): Power optimized waveforms are energizing RF signals that are tailored for collection by energy-harvesting circuits [Tro09]. Current RF energy-harvesting circuits, such as those used in RFID systems, are energized by pure sinusoidal waveforms, which can be shown to result in very low conversion efficiencies for a given average waveform power. POWs enhance conversion efficiency by using special band-limited RF waveforms with high peak-to-average ratio.

Retrodirective Array Phase Modulator (RAPM): RAPM electronic circuitry uses a passive retrodirective array with phase modulation to send reflected signals from a transponder to a reader with maximum possible signal gain. Developed in 1955 by L.C. Van Atta, a conventional retrodirective array (RA) holds the unique property that any impinging waveform is reradiated back in the direction from which it arrived with maximum gain; it is the RF analog of an optical corner reflector [Att59]. This property improves communication and removes the necessary array hardware required for active beam-steering.

It is also possible to alter the phase of an incoming wavefront by switching between different predetermined line lengths connecting the antenna pairs. By switching these line lengths of the antenna pairs simultaneously, one can then achieve M-ary phase shift keying of the reradiated wave where M is the number of line segments. Figure 1a demonstrates the phase modulation block for an antenna pair in a RA. Each additional antenna pair would consist of the same block. The retrodirective array phase modulator (RAPM) shown in Figure 1a is capable of performing quadrature phase shift keying. By using a microcontroller, two switches can be controlled simultaneously to switch between lines lengths of: \( \frac{\lambda}{4}, \frac{\lambda}{2}, 3\frac{\lambda}{4}, \) and \( \lambda \), where \( \lambda \) is wavelength of radiation. These electrical line lengths induce phase shifts in the reradiated signal of 90°, 180°, 270°, and 360°, respectively.

Another unique attribute of a RAPM tag – the “stop sign” effect – is illustrated in Figure 1b. Since the RAPM antenna array acts much like optical corner reflectors, it reflects power with high gain towards the source and nowhere else, much like a stop sign illuminated by a point source of light. Thus, off-source viewing of the reflector tag will perceive a very weak signal originating from the RF tag, making the modulated information undetectable for most eavesdroppers. However, the retrodirectivity imparts an effective radar cross section to the transponder that is much larger than its actual physical size.

Staggered-Pattern Charge Collector (SPCC): One method for increasing the power available to a passive, energy-harvesting RF tag is to add more antennas. On a passive transponder, hard-wired electrical connections between antenna array elements could achieve significant gains, but the resulting gain in one spatial direction will come at the expense of gain in all of the other directions – highly impractical for RF tags that are not placed with a priori knowledge of a broadcasting power source. However, a clever choice of sub-array electrical connections on a multi-antenna backscatter tag circumvents this problem if each sub-array achieves gain in a certain direction, while all the sub-arrays collectively cover a wide spatial area. This is the idea behind the staggered pattern charge collector (SPCC) [Dur10].
Pattern Strobing: Spatial strobing of transmitted UHF/microwave power is a method for increasing the amount of power into a passive, energy-harvesting UHF/microwave RF tag. This is all accomplished without increasing overall transmit power or regulatory restrictions on transmission. Problematically, antenna gain in one direction comes at the expense of gain in another direction, so proper microwave excitation of passive devices would require the pattern be *strobed* through space, by either sweeping or stepping the antennas main pattern lobes. At first, this may seem like a zero-sum exercise: increasing the gain by a factor of $A$ would require increased sweeping to maintain complete coverage, reducing the duty cycle of excitation by an equivalent factor of $A$. The nonlinear charge pump circuitry operates more efficiently under higher excitation levels with increased duty cycles than under continuous excitation of the same average power level. One might consider pattern strobing the spatial equivalent of a power-optimized waveform [Tro09].

Acyclic Spread Spectrum Modulation: The use of spread spectrum provides resistance to interference in conventional wireless links as well as microwave/UHF backscatter links [Dur08]. Graf showed in [Gra10] that variants of spread spectrum signaling codes can be used by low-power transponders to conserve power and enhance the throughput. This acyclic spread spectrum introduces gaps between data symbols, allowing energy-harvesting circuits to “catch their breath” without compromising on signal acquisition.

These advances promise enhanced ranges for RFID tags and other demonstrated passive sensors [Sam08].

3. References


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