TABLE I. MEASUREMENT RESULTS, CORRECTED WITH LOG AMP CORRECTION FACTOR, WITH COMPARISONS TO PRIOR WORK

	Continuous Tx.	WiFi AP	
	2 m	2 m	10 m
Peak Power	3.8 μW	36.6 μW	5.94 μW
Corrected Avg. Power	2.7 μW	0.052 μW	0.011 μW
Uncorrected Avg. Power	-	0.14 μW	0.03 μW
Visser [5], Peak Power	1–10 μW/m^2	8 m	
Bouchouicha [6], Avg. Power	12.5 pW	(unknown distance)	
Ishizaki [10], Avg. Power	5 μW	50 cm	

deliver small but sufficient power to be able to harvest for wireless sensor node systems.

B. Energy Harvesting Time Estimates to Transmit Sensed Data

Based on these encouraging results, we estimated the harvesting time required to store up sufficient energy for a sensor node to transmit a RF packet containing sensor data. For this exercise, it is assumed that the actual act of sensing consumes a small fraction of the power required to transmit the results, and thus has negligible impact to the harvesting time measurements.

For these estimates, we computed the energy required to transmit a 432-bit UDP packet using conventional RF communications. We considered only packet transmission time, not bootup, link establishment, or shutdown, because of the system variability. We assumed a 40% energy harvesting efficiency. The harvest time estimates are shown in Table II.

V. CONCLUSION

An RF energy measurement system was built and tested to measure ambient RF energy in the 2.4GHz ISM frequency spectrum. Two complementary measurement devices were used, a spectrum analyzer (frequency-selective but slow) and a log amp (wide-band but fast). The frequency-specific data from the spectrum analyzer was summed and averaged, then corrected with concurrent wide-band measurements from the log amp. Data was captured in a typical office environment at different locations and varying times. The processed data measurement results show that RF energy harvesting in the 2.4GHz ISM band is feasible with a sufficiently patient duty cycle.

TABLE II. ESTIMATED DURATION OF RF HARVESTING AT AVERAGE AMBIENT RF ENERGY DENSITY REQUIRED TO TRANSMIT A 432-BIT UDP PACKET

Communication Method	Example Radio	Transmit Energy	Distance from AP 2 m	10 m
Low-power WiFi	Ozmo 2000	71 μJ	1 hr	4.4 hr
Zigbee	TI CC2431	154 μJ	2 hr	9.6 hr
BT-LE	TI CC5240	26.5 μJ	0.35 hr	1.7 hr

VI. FUTURE WORK

In the future, we plan to capture RF energy measurement data in a greater variety of locations. We also plan to develop a measurement system that is more portable, that can be used in public places such as airports, homes, conferences, and even outdoors to evaluate energy densities in a wider variety of "Wi-Fi enabled" locations. We would also like to develop an RF energy "heat map" so we can visualize weak and strong locations for a sensor node energy harvesting system. Such a "heat map" can be used to adjust placement of access points for more effective wireless sensor node functionality.

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