**PLoRa:**

The Internet of Things (IoT) concept describes a network of wirelessly connected objects, enabled by RF tags, sensors, software and other technologies. There are three properties cited as baseline requirements for realizing the IoT vision at the physical layer; Devices should be battery-free, long-range, and capable of harvesting ambient signals for power and communication. PLoRa, a passive long-range data network, strives to fulfill these three requirements while maintaining compatibility with existing LoRa devices.

The feature distinguishing PLoRa from other LoRa network schemes is its ability to modulate ambient LoRa traffic to transmit data. While minimizing the use of hardware and power in data transmission, this technology exploits uplink and downlink piggybacking opportunities to extend its communication range to a maximum distance of 1.1 km. By modulating its antenna impedance, the PLoRa tag can return an uplink signal that is at a different frequency than the gateways downlink transmission. The paper introduces 4 primary contributions:

1. Sample rate reduction and cross-correlation for packet detection in a low power environment
2. FSK modulation of ambient downlink and uplink LoRa chirps to generate a new standard downlink/uplink LoRa chirp, piggybacking other LoRa tags with little concern for interference
3. Energy management hardware to mitigate node state transitions, avoiding energy starvation which would ultimately lead to loss of data stored inside the volatile memory
4. A light-weight backscatter decoding algorithm with MAC-layer protocol that allows the PLoRa tag to co-exist with active LoRa nodes.

A prototype is implemented using a four-layer printed circuit board using commercial off-the-shelf components and a Microsemi IGLOO nano AGLE600V2-FG484I FPGA with a 28 nm baseband processor. The energy harvester consists of a five-stage voltage-doubling amplifier HSMS-286C, a photovoltaic charger and a super energy storage capacitor SCDM3R3224. The transmitter uses an ADG902 RF switch. The majority of power consumption is due to the processor, which consumes $220\ \mu W$ of energy.

**Design:**

Unlike conventional backscattering systems, the passive nature of PLoRa tags necessitates that packet detection exploit ambient signals as excitation signals. A reduction factor of 480 in the normal sampling rate of the ADC was shown to achieve a minimum power consumption and optimal success rate over a 50 m distance. This reduction in sampling rate is possible for packet detection as there is no decoding of information needed and hence, detection is not bound by Nyquist sampling limit. The repetition of the up chirps in the LoRa preamble is exploited; Only one of the up chirps is stored inside of the low-power FPGA and it is repeatedly correlated with the incoming sequence until a match is detected. A blind chirp modulation algorithm is implemented because the incoming data chirp is not known in advance. The incoming LoRa chirp is shifted in frequency by $\pm$BW/2 and the in-band part of the two shifted chirps is spliced. The resulting chirp occupies the entire BW and is a new standard chirp by nature, avoiding channel interference. The decoding of the passive LoRa signal is done by observing the location of the FFT peaks of the products of the active and passive LoRa chirps with the LoRa down chirp. Chirp "0" is decoded if the location of the peaks is below a pre-determined threshold, while chirp "1" is decoded if the peaks are separated further apart than that threshold value. The threshold is empirically set to seven FFT bins for optimum demodulation accuracy after conducting several tests in different environments.

**Implementation and Evaluation:**

The performance of the PLoRa system is evaluated in both outdoor line-of-sight and indoor non-line-of-sight scenarios. To evaluate the effective backscatter range, the distance between the tag and source is varied. It was found that, when placed close to the source in an outdoor setting, the PLoRa tag can effectively backscatter signals to a receiver 600 m away. The experiment is repeated in an indoor setting and it is shown that the backscattered signal can penetrate two concrete walls when the tag is placed near the receiver. The signal is only strong enough to penetrate one wall as the distance is increased to 10 m. Field study experiments also examine the bit rate error as a function of distance in different weather conditions, and the tag's performance in a LoRa WAN setting.

To further justify the system performance, effective packet detection range is studied. Received signal strength at the PLoRa tag versus the distance from the excitation source is the metric used to quantify this. The PLoRa tag achieves a maximum detection range of 50 m.

**Discussion:**

During the class discussion, students acknowledged the novelty of the concept and credited the authors for following through with a complete prototype implementation. The dual fold purpose of the FSK modulation provoked further discussion. It cleverly avoided channel interference, while also being compatible with CSS modulation commonly adopted by active LoRa tags. However, most students were confused as to how the extended range of the PLoRa tags is achieved, since the reported packet detection range was only 50 m. PLoRa relies on opportunistic piggybacking and compatibility with active LoRa nodes for long range extension up to 1.1 km. A more accurate term, "extended backscattering coverage" was suggested to avoid this ambiguity. The tradeoff between the tag-to-node distance and the tag-to-gateway range was discussed with Dr. Shangguan, and he shared insights on potential means of optimization.

A brief discussion was held about the potential to charge the capacitor continuously without allowing it to fully discharge. Dr. Shangguan mentioned that, although this concept was considered, any attempts resulted in high losses and inefficiencies within the circuit.

Design limitations that were highlighted during class included the multi-node performance of the PLoRa tag. This raised concerns, particularly that the evaluation had only been done with a single active LoRa tag and PLoRa node pair. It was also mentioned that the LoRa packets do not have error correction codes. The design used readily available clock signals from the FPGA to generate the shift frequencies needed for the FSK modulation. In integrated implementations however, these would need to be provided using PLLs.

The PLoRa design is an exciting take on ambient backscatter technologies. This paper attempts to make incremental improvements to IoT systems and devices by addressing the needs for battery-less, long range tags which are capable of ambient signal excitation.