A Scalable and Robust Prototype of Sensor Network for Real-Time Street-Level Flood Measurement

Report Submitted to the Houston Solutions Lab at Rice University

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1. Introduction

Houston frequently experiences severe flooding in water-accumulating areas, such as bayous and flood plains. High-rainfall events have caused unexpected flooding in many residential areas as well. Hurricane Harvey in 2017 is the most obvious example, but in the preceding 2 years there were two additional so-called “500-year floods” that produced unexpected damage. Improved urban planning based on accurate flood models can mitigate future food damage. Flooding from bayous overflowing can be reasonably well predicted, but flooding due to runoff over mixed urban environments requires computer models calibrated with real-world data. Thus, there is a need for a network of flood-water-level sensors to be placed in strategic areas in order to calibrate flooding models.

We have built, tested, and deployed a proof-of-concept network of flood sensors around Rice University and in the City of Houston. This Report summarizes our results for the last 15 months, including the award period from Aug. 2018-Aug 2019. The system comprises a network of water-level sensors that can be placed street-side or in drainage ditches. Our network is accurate, low-cost, scalable, and mostly functions off-grid by means of solar-powered sensors. The network reports water levels at ~5-minute intervals and can be read from a web browser anywhere with an internet connection. Because it is effectively real-time, our system may be useful for evacuation or emergency response. Our results are promising and the network is being used as a basis for further funding proposals, including one currently underway to NSF.

2. Overview of System

The table below summarizes the key performance requirements of our system and our results. Version 1.5 was deployed in the Harris Gully area of Rice from June-August 2019, and then moved to a flood-control ditch in the Alief area in August 2019. Version 2.0 is not yet deployed but exhibits superior performance as shown in Table 1 below. The Bill of Materials and cost for both systems can be found here.

Table 1: System performance criteria and results

Criterion	Result	Met?
Off grid	Sensors solar powered with ~ 2 month battery backup Relay node (v1.5) requires grid power with ~ 2 day backup	yes
Low cost	Sensor $420; Relay $240 + $20/mo (v.1.5) Sensor $480 + $4/mo; Relay N/A (v.2.0)	yes
Scalable	Relay ~ 0.7km radius (v. 1.5) Independent cellular connection per sensor (v.2.0)	yes

Live data	Updates every ~ 5 minutes, viewable from website	yes
Data archiving	History viewable or exportable to .csv file	yes
Accuracy +/- ½	WIth temp. correction ¼"; without, 1.5"	partially
Weather- and vandal-proof	Weatherproof box high on pole; vandal-resistant rubber tube + PVC pipe casing for sensor	yes

2.1 Deployed system (v.1.5)

The deployed system, version 1.5, has a hub-and-spoke architecture. Each Sensor Node is attached to a pole with a pressure sensor at ground level and a wireless transmitter 8-10 feet in the air. A number of sensors are all connected to a single Relay Node (hub) via a long range, low power radio link("LoRa"), which then sends the data to the cloud via a cellular data link. The Sensor Nodes must be within about 1km of the Relay, depending on intervening buildings or vegetation, but the cellular link can be many km from the nearest cell tower. A Relay Node can support dozens or even hundreds of Sensor Nodes although we envision that 4-5 Sensor Nodes per Relay will provide sufficient coverage of flood-water levels within a 1km radius of the Relay Node. Measurements are made & transmitted approximately every 5 minutes. Once the data has been transmitted over the cellular link, it appears in the cloud and can be viewed from any web browser. We have also developed a graphical visualization tool. The Relay Node bill of materials (BOM) cost is about $240 and the Sensor Node (v.1.5) BOM cost is about $420. There is an operational expense of about $20/ month for the cellular data link.

The Relay and Sensor nodes are both placed in weather- and UV-resistant plastic boxes that are designed for holding cable TV equipment on telephone poles. Placing both Relay and Sensor on top of poles helps with reception range and reduces their susceptibility to vandalism. Sensor nodes include a differential pressure sensor that is placed at ground level. It measures water level via the pressure of the column of water. The cable from box to sensor is proected with a vandal- and UV-resistant rubber tube. The sensor element itself is protected inside a casing of PVC pipe with holes drilled in one end to allow water entry. The sensor element exhibits a slight variation with temperature which on hot days corresponds a diurnal baseline shift of about 1.5" of water level. This can be modeled out to some extent, and we have verified a hardware fix that will be deployed in Version 2.0 to eliminate this error. The Sensor Nodes are equipped with solar panels which are also mounted on the pole. The solar power is sufficient to maintain charge on a high capacity battery from which the sensor draws power. The battery can last for about 2 months at the rate of power draw from the system so extended periods of cloudy weather will not stop the system from working. The Relay Node does require electrical power from the grid (about 1W on average). It has been a simple matter to get permission from the City of Houston to tap power from traffic lights.

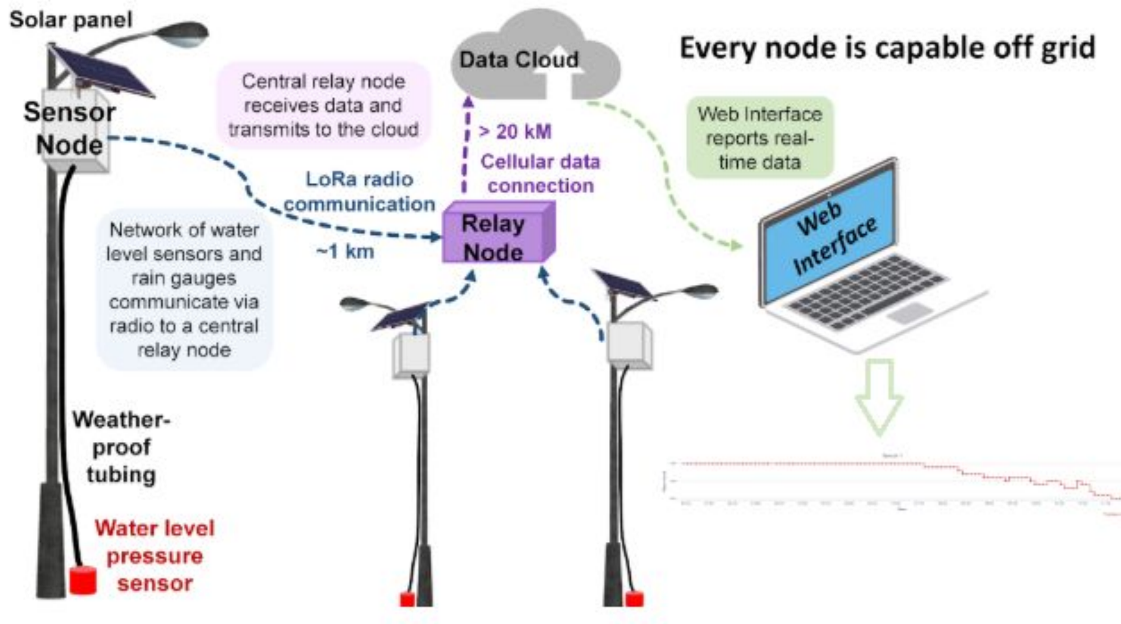

Figure 1. System schematic for v. 1.5 using LoRa link + Relay

2.2 Next-gen system (v.2.0)

Our next generation system (Version 2.0) has Sensor Nodes that communicate directly over the cellular network using the NB-IoT standard and provides several improvements over v1.5. The pressure sensing elements are identical in form factor, resolution, and dynamic range. We have incorporated a temperature sensor that removes the diurnal error. The direct cellular communication removes the need for the Relay Node entirely, and allows Sensor Nodes to be placed anywhere in a city. The Sensor Nodes draw more power in this scheme than in Version 1.5 because they are using a higher-power radio link, but the power from the existing solar panel is still allows indefinite off-grid operation and at least 1 month of battery backup. The Sensor Node costs about $490 in v.2.0. There is a small additional operational expense of $3.66/ month because each node must have a separate data link. In volume it would probably be possible to reduce this cost significantly. Additional advantages in v.2.0 stem from the use of a licensed radio band: first, interference from other transmitters becomes less of a concern, and second, standard cellular protocols prevent eavesdropping or spoofing of data. Version 2.0 has been tested in the laboratory and we intend to deploy it starting in Fall 2019. Figure 2 shows a schematic of the Version 2.0 system, and Fig. 3 shows a comparison between v.1.5 (LoRa) and v.2.0 (NB-IoT).

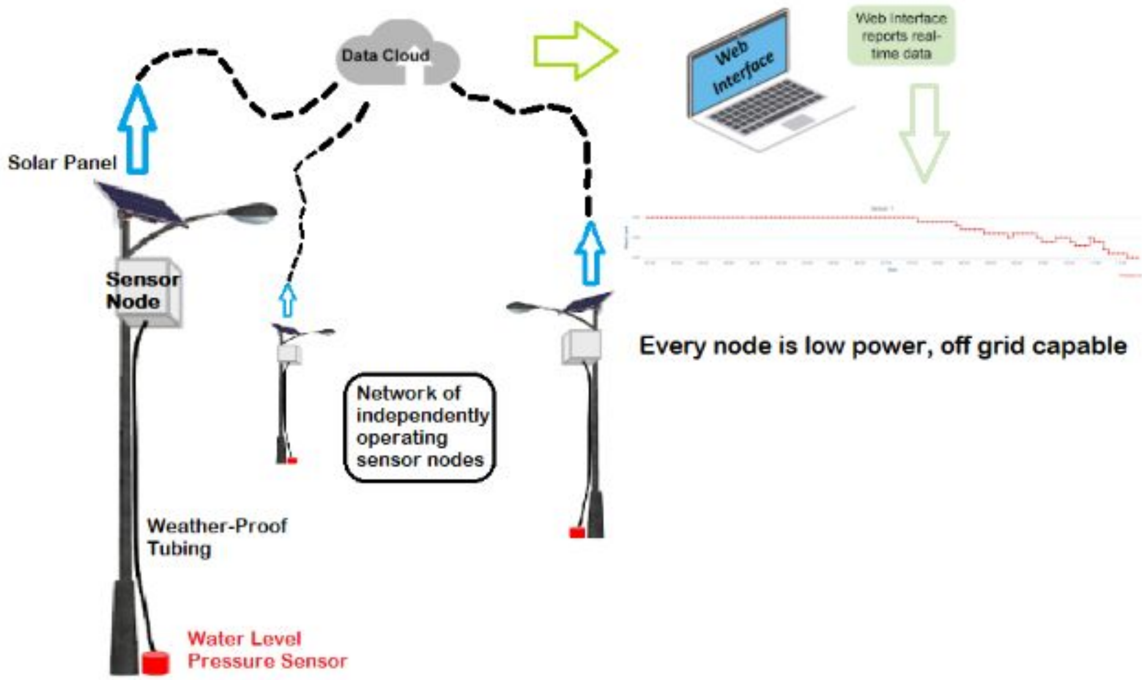

Figure 2. System schematic for v. 2.0 using NB-IoT direct cellular connections

LoRa	NB-IoT Cellular
○ Sensor nodes are EXTREMELY low power	○ Sensor nodes are independently deployable, more flexibility in deploy locations
○ System is slightly less expensive than cellular model	○ Only requires cellular connection to transmit
○ No packet loss or missed transmissions	✖ Nodes are more slightly more power hungry, nodes last ~month without direct sunlight
✖ Subject to interference (unlicensed band)	✖ Current bugs exist that cause missed data packets (~95% success)
✖ More complex deployment (Relay must have LoS with nodes, relay requires a constant power source)	
✖ Relay is subject to many bugs	
Relay Cost: **$240** Node Cost: **$420** Operational Cost: **$20/month** for relay serving 4 nodes	Node Cost: **$490** Operational Cost: **$3.66/month** per node

Figure 3. Comparison of v.1.5 (LoRa) and v.2.0 (NB-IoT) systems

3. <u>Data Access</u>

Both system models upload data to the Hologram Cellular cloud, an IoT dedicated cellular platform. Hologram also provides the SIM cards that the nodes use to get access to the cellular network in order to upload data to the cloud. The Hologram web interface includes functionality to view the raw data and help debug when and why transmissions go awry. Using Hologram's cloud services, we automatically forward our data to the ThingSpeak IoT database. ThingSpeak is another IoT focused web platform which allows us to store the data in an easy to access format, generate graphs that are an excellent visualization of the data over time, and use MatLab to analyze and manipulate our data. The data visualizations generated by ThingSpeak are also straightforward to incorporate into a website. Fig. 4 shows a sample of data as visualized via ThingSpeak (note this is sample data, not an unphysical rainfall event.)

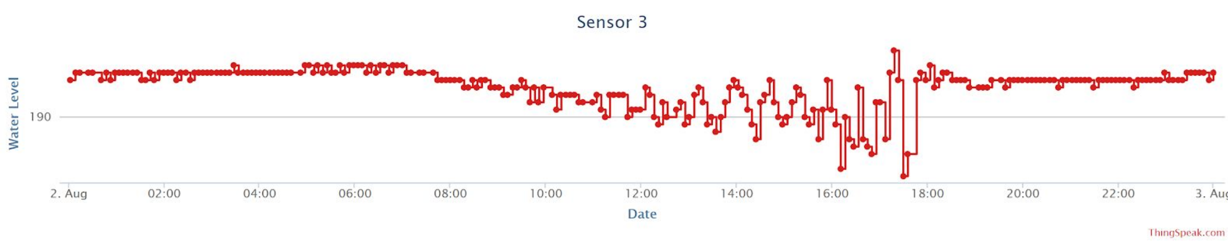

Figure 4: ThingSpeak Sample Graph

4. <u>Results and Deployment</u>

On Campus testing: During the development process we would place testing nodes outside on light poles located near the building we are working in order to test their reliability and accuracy in conditions that were a better approximation of what they would need to be designed to face than anything we could simulate inside. These tests helped prepare us for deployment and were extremely effective in allowing us to identify and correct problems with our system. Halfway through the summer we reached the point where we believed the LoRa model system was reliable enough to be ready for deployment. At this point we simulated a deployment by setting up an entire LoRa model network in the water detention area on the south side of the Rice campus, and then leaving it completely untouched for weeks. This test deployment was a success as the entire network was still functional 5 weeks later when we took it back down to prepare for an actual deployment in Houston. If there had been a flood during this time, the sensors would have detected it.

Deploying in the City of Houston: The ultimate goal of this project is to deploy sensors across the city of Houston. This summer we attempted to deploy one network in a neighborhood. The selected location was along Brandon Street and Comal Street between Reed Road and Bellfort Street. This location was selected because it was near a future City of Houston improvement project that would change the way water was able to flow during and after a rain event .We wanted to use the system to gather data on the effectiveness of this project. In order to deploy we needed to secure permission to use some kind of elevated power supply for the relay, and permission to mount the sensors to the existing poles along the roads. We successfully obtained permission to use power from the traffic lights at nearby intersections. However, Centerpoint Energy denied our request to attach anything to their poles, and they own most of the tall poles in convenient locations next to streets everywhere in the City. This pushed back city deployment from July to August.

We eventually found a satisfactory alternative site. We deployed two Sensor Nodes in a flood-detention area in the Alief neighborhood of Houston, near Brays Bayou. We chose this area because (1) It is owned by the City so we had permission to put sensors on the land. (2) There is a traffic light within about 800 m that is owned by the City for which we had permission to install a Relay Node. (3) The area is slated for a flood-improvement project according to the City's SWAT database. Steve Costello, the Chief Resilience Officer for the City of Houston, expressed a desire for sensors to be placed so as to give "before" & "after" data related to flood projects. Fig. 5 shows the deployment area just off Cook Road. The Relay Node is attached to the traffic light at the corner of Beechnut Street and Cook Road.

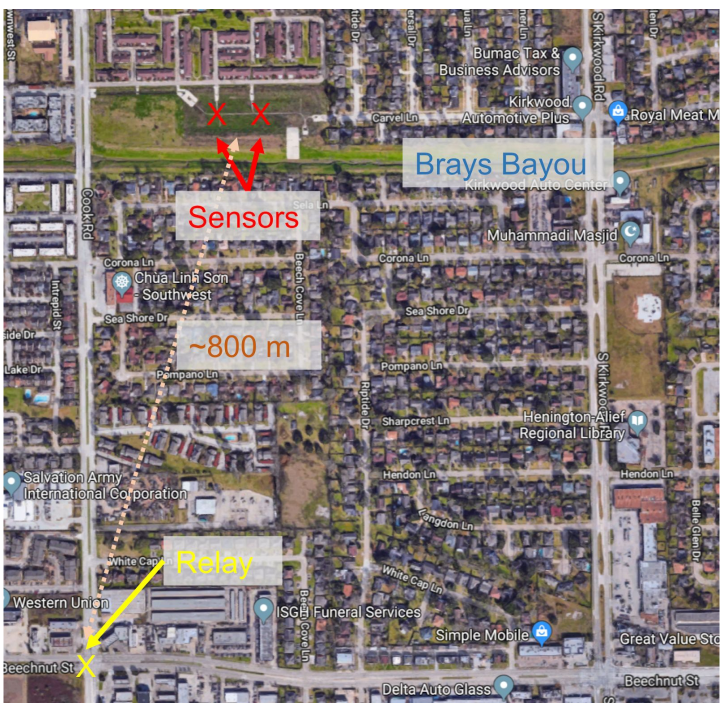

Figure 5. Satellite photo of deployment area.

The system was activated on August 26. So far there has not been enough rain for the sensors deployed in the City of Houston Alief area to register any water yet. We are awaiting a large but hopefully not *really large* rain storm.

5. Next Steps and Conclusion

Between August and Dec. 2019 we intend to replace the Version 1.5 Sensor Nodes deployed in Alief with Version 2.0 Sensor Nodes. We also plan to deploy additional v.2.0 Sensor Nodes in other strategic locations to be determined by consultation with the City of Houston. A team of new and continuing students will work on the project this fall.

In summary, we have delivered essentially everything we committed to in our original proposal. We have developed and deployed a distributed wireless network of flood-water-level sensors. The sensors are low-cost and work off-grid with zero maintenance. The data is automatically uploaded to the cloud where it is available in near-real-time on any web browser. We have proven the system's capability on the Rice Campus and have deployed to a target area identified in collaboration with the Mayor's Office of the City of Houston. We are pursuing continuous improvements in the system and are using this proof of concept as the basis for an NSF proposal.

6. Acknowledgement

We gratefully acknowledge the support of the Houston Endowment, Inc.; this work is made possible in part by the support of the Kinder Institute for Urban Research, the Office of Sponsored Research, and the Ken Kennedy Institute for Information Technology at Rice University under the Houston Solutions Lab project.

Appendix: Budget and Expenditures

The original budget of $73K was allocated as follows.

Item	Cost	Extended cost
Summer or Fall Student #1 (URA): Sensors	$8,000	$8,000
Fall or Spring Student #2 (URA): Sensors	$8,000	$8,000
Student #3 (GRA): Models	$24,000	$24,000
Robust sensor network development and assembly plan	$10,000	$10,000
Sensor node parts	16 @ $750	$12,000
Sensor assembly costs	16 @ $250	$4,000
Maintenance engineer	100 hrs @ $50/hr	$5,000
Wireless and web services	8 months @ $250/mo	$2,000
Total		**$73,000**

To date the expenditures have only been about $16, per Susan Lock. This is mostly because several summer students started working on the project in May 2018 although the grant funds were not available to the team until August 2018. We have also charged the graduate student support in 2018 and 2019 to different accounts on a temporary basis. We have agreed with the funders on a zero-cost extension lasting for a few more months while the next round of deployment is completed. During this time we we will rebalance our accounts to apply the proper expenses to this grantt.