Performance of Outdoor Wireless Internet Micro-Hubs

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Abstract

An experimental node-based wireless 802.11 b/g/n mesh network providing Internet access to users in Cambridge, Massachusetts, was developed at the Massachusetts Institute of Technology while complementary thermal modeling was conducted at the University of North Texas. Netgear WGT634U 108-megabyte-per-second wireless storage routers mounted within environmental enclosures at outdoor and indoor locations across the Cambridge coverage area serve as signal repeater nodes for the network. Denton, Texas, is a promising site to deploy a wireless network similar to the one in Cambridge. However, the ambient outdoor conditions in Denton differ from those in Cambridge and may exceed the operating envelope of the repeater nodes if not mitigated by well-designed environmental enclosures. By instrumenting a sacrificial node with thermocouples and baking it in a furnace, we determined that the node's built-in safety shut-off temperature is 130 ± 3 °C and that the temperature at which irreversible damage occurs is in the range of 135 °C to 145 °C. By synthesizing this data with historic regional ambient temperatures through heat transfer modeling, we conclude that node thermal failure cannot be induced by high ambient temperature, provided that the node enclosure is designed with sensible thermal management precautions. Additionally, we measured the maximum viable distance between a node and a receiver. Beyond this maximum separation distance, low signal fidelity yields high packet losses (50% packets lost) and data transfer rates inferior to those of dial-up Internet (less than 56 kilobytes per second). Using a global positioning satellite system, we found maximum ranges for inter node communication both via a line of sight and through a building wall. These ranges were 183 ± 4 meters and 49 ± 4 meters, respectively. These shut-off temperature data and signal range data guide the design of future outdoor node enclosures and indicate the inter node spacing necessary to assure fast, reliable WiFi Internet coverage in Denton.

Introduction

An increasing array of electronic devices can access and use the Internet, and device utility increases where wireless access is available. To enable wireless Internet access for citizens and their electronics, several cities (notably Philadelphia and San Francisco[1]) have attempted deployment of so-called municipal broadband networks. These networks are cheaper, faster to deploy, and easier to access than their hard-wired counterparts. However, few cities have succeeded in creating wireless networks on a municipal scale, especially when a corporate partner builds the network at no cost to the city in exchange for advertisement rights on the network.[2]

Juxtaposed against the free municipal broadband network model embodied by city-corporate partnership, researchers at the Massachusetts Institute of Technology (MIT) formed the Roofnet group to develop a simple, economical, expandable, and administrator-free method of deploying a large-scale wireless Internet network in an urban environment[3,4,5]. The resulting experimental node-based wireless 802.11 b/g/n mesh network now provides Internet access to users in Cambridge, Massachusetts.[6] A community-built, -owned, and -operated free wireless network based on Roofnet technology is also now being deployed in the Dallas/Ft. Worth area.[7] Commercially available Netgear WGT634U 108-megabyte-per-second wireless storage routers[8] mounted at outdoor and indoor locations across the coverage area serve as signal repeater nodes for the network. Although generally successful, the Roofnet network appeared vulnerable to high temperatures on the hottest summer days in Cambridge.[9] Roofnet contacted heat transfer and thermal management researchers at the University of North Texas (UNT) to determine how susceptible the Netgear WGT634U routers are to high temperature. This collaboration also determined that Denton, Texas, is a promising site for deploying a wireless network similar to the ones operating in Cambridge and Dallas/Ft. Worth.

Certainly the ambient outdoor conditions in Denton differ from Cambridge and may require more extensive thermal management. To determine the viability of Roofnet network deployment in Denton, we measured the failure temperature of a sacrificial Netgear WGT634U router by instrumenting key hardware components with thermocouples and baking the router in a furnace. The measured failure temperature was compared against the highest recorded temperatures in Massachusetts and Texas to ascertain component survivability in both locations. The router's performance just before temperature-induced failure was examined to determine whether high-temperature exposure degrades performance. Additionally, the maximum line-of-sight and through-wall distances between a wireless node and a receiver were measured. Beyond a maximum separation distance, low signal fidelity yields data transfer rates inferior to those of dial-up Internet.

The data gleaned from these experiments is being shared with MIT and the Roofnet Community. This information is important for wireless network planners because it will influence next-generation hub design and deployment in future municipal outdoor wireless networks.

Methods

The failure temperature of a router node is the temperature at which the router ceases to emit a wireless signal. A sacrificial node was selected at random from a lot of Netgear WGT634U routers supplied to UNT by Roofnet. This node was instrumented with three Omega 5SC-GG-K-30-36 K-Type thermocouples read via an Omega HH147 hand-held data logging thermocouple reader. The three thermocouple beads were placed in physical contact with the router processor, radio card, and random access memory (RAM) chip, respectively (the three thermocouple wires are visible in Figure 1). For the processor, the rigidity of the thermocouple wire was used to insure physical contact, but the thermocouple bead was not soldered or otherwise physically connected to the processor. Scotch® tape was used to affix thermocouple beads to the other router hardware components. The processor, radio card, and RAM chip were specifically selected for temperature interrogation because failure of any of these critical elements would cause the router to cease functioning. With the thermocouple beads in place, the plastic case was secured back into the router.

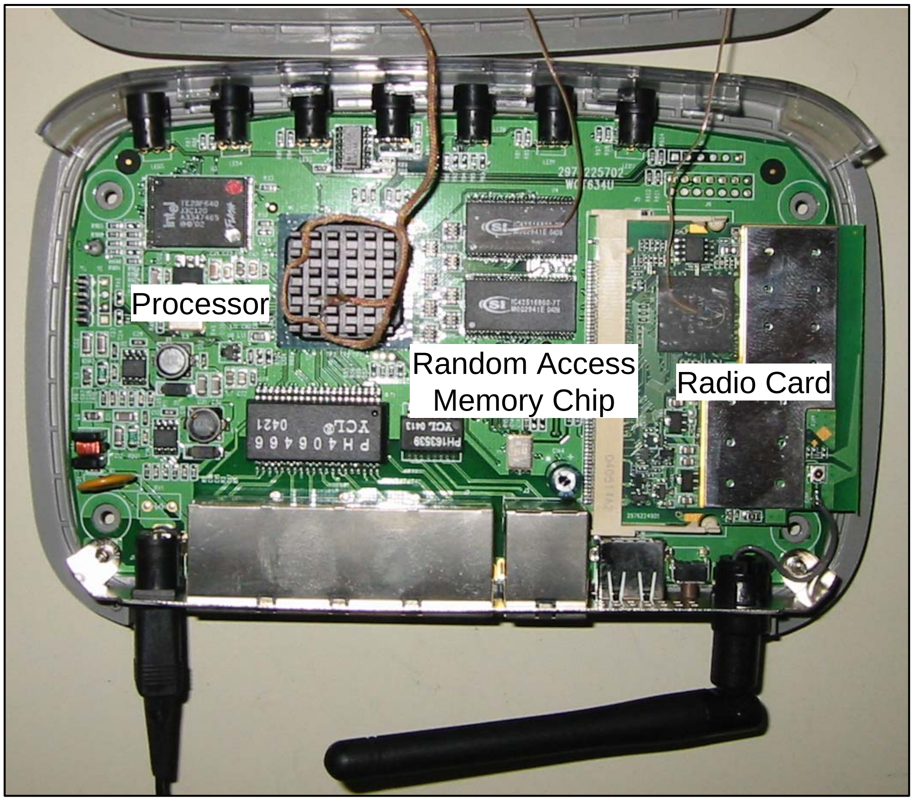

Figure 1. Thermocouple Instrumentation Scheme to Measure Component Internal Temperatures within Netgear WGT634U Wireless Router.

A Toastmaster™ model 398A commercial toaster oven (rated for 1680 watts at 127 volts) provided the heated environment for router failure testing. This oven was originally for food preparation; unlike a laboratory furnace, it has no mechanism to assure a uniform spatial temperature. Moreover, the primary heating elements are cylindrical irradiative heaters that can glow with heat even before the inside of the oven becomes too hot to touch. Thus, the primary heat transfer mode within this oven is radiation. However, for these experiments, the mode and rate of heat transfer were not critical because the primary focus was router failure temperature.

To determine the spatial temperature gradient magnitude inside the oven, we measured the operating temperature of the oven heating elements by placing a K-type thermocouple in proximity to one of the four toaster heating elements, with the wire leads wrapped five times around the element to mitigate fin effect. Upon reaching operating temperature, the four toaster heating elements cycle via on-off control between 250 °C and 282 °C. A pair of Extech MM570 power meters recorded consumption of 12 amperes at 113 volts (approximately 1356 watts) for the toaster while the heating elements were on. To determine where to locate the router within the oven to reduce temperature gradient, we instrumented the empty oven itself with three Omega 5SC-GG-K-30-36 K-Type thermocouples placed at the front, middle, and back of the oven approximately 8 centimeters from the surface of the baking tray. Measuring the relative temperature recorded at each of these locations enabled assessment of the temperature gradient inside the oven. At steady state, a 25 °C spatial gradient in temperature was observed between the front and the rear of the oven. The measured temperature at oven's front (near the door) was 156 °C and 128 °C at the back. These data indicated that placing the sacrificial router in the center of the oven, where the temperature was nearly the arithmetic mean of the extreme locations, would produce the most consistent temperature during the router's exposure to high heat.

We determined that dwelling in the enclosed interior of the oven does not impact the steady-state operating temperature of the router. Prior to failure testing, the router was turned on and allowed to sit overnight inside the oven while the oven was off. This process assured that the entire system was thermally equilibrated. The processor temperature of the running router inside the oven was compared to a router outside the oven that had been cold-started. After an hour, the cold-started router processor matched the temperature of the router processor in the oven running overnight (about 50 °C) within the measurement error of the instruments. This test confirmed that the presence of the oven, while turned off, had no impact on router steady-state temperature.

The poor on/off temperature control scheme offered by the Toastmaster oven necessitated orientation tests with the oven empty to determine a consistent heating method. Prior to the router failure experiments we exercised the empty thermocouple-instrumented oven through a series of different warm-up protocols to determine a heating method that would generate the most linear temperature increase for the router experiments. Our tests showed that turning the oven to half its maximum power for 5 minutes, then turning to full power, provided a nearly linear temperature increase of approximately10 °C per minute inside the oven over the duration of the test until steady state temperature is reached.

To conduct router failure tests, an actively running router was placed inside the oven. The prescribed oven temperature-ramping scheme was followed to give linear temperature increase, and the router was allowed to heat up until it ceased to function. During the experiment, router function was monitored wirelessly via a Toshiba Satellite P105-S9312 laptop located in direct line of site 1 meter away from the oven-router combination, and temperature was monitored with the Omega HH147 hand-held data logging thermocouple reader. The laptop ran a continuous ping test for the router's address at a rate of 1 ping per second and had a packet size of 56 bytes. The intention of this test was to monitor the temperature at which loss of ping packets rendered the router signal unusable; in other words, we assumed that router performance would degrade as temperature increased until the failure temperature was reached. As discussed in the Results section, and shown in Figure 2, the loss of ping packets was not gradual as temperature increased but rather instantaneous at a specific temperature. Vertical lines in the graph indicate dropped packets, where the latency was recorded as infinity.

Since the router returned to normal function after cooling down, the test procedure was repeated four times with the same router. As reported in the Results section, the router's external plastic router case began to deform at a lower temperature than the router shut down. So, two replicate runs were made with the router inside its original case, and two additional replicate runs were made with the internal router hardware exposed and sitting atop a ceramic brick.

Results

The solid-state router component that stopped functioning first owing to high temperature was the processor. Had the radio card failed, the router would have been seen to visually continue to function (i.e., the lights on the front panel would have continued flashing), but no wireless signal would be received by the laptop. Had the RAM failed, the router would have exhibited erratic wireless signals and packet loss prior to total failure. Processor failure should have resulted in total, instant router shut-off accompanied by simultaneous loss of wireless signal. This behavior is, in fact, what was observed, as is shown in Figure 2. The wireless signal's fidelity, or 'ping time,' remained a nearly linear up to the point of failure.

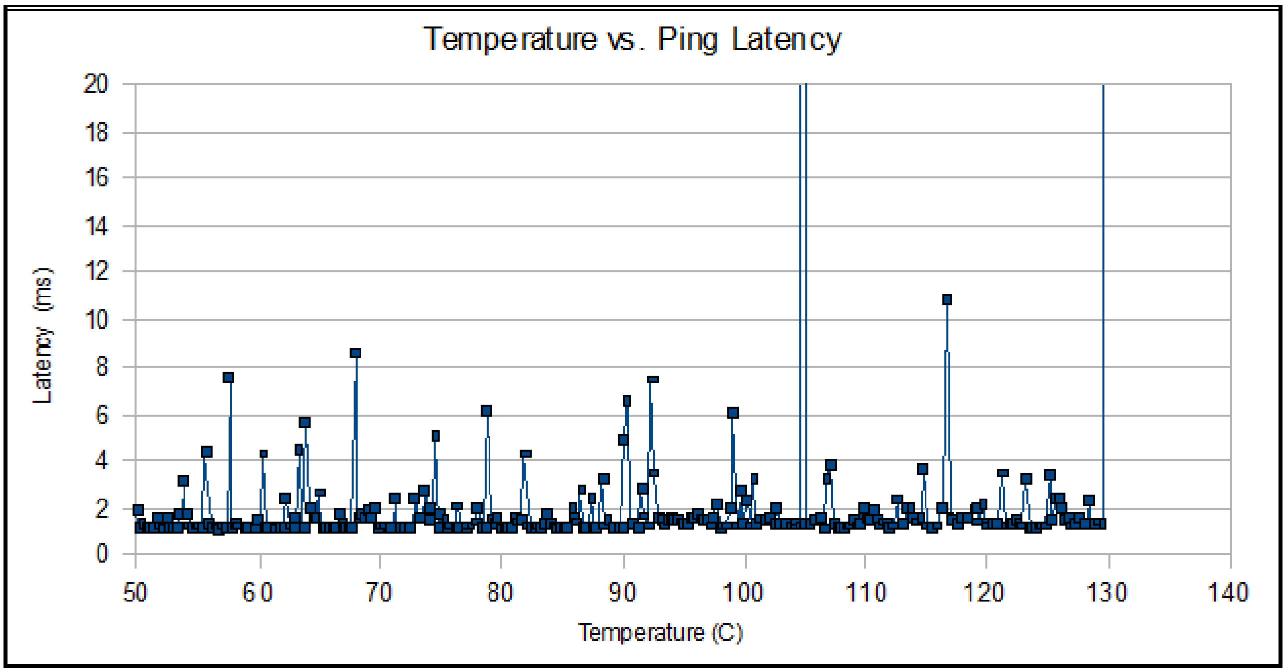

Figure 2. Ping Latency Versus Temperature during Netgear Router Heating. Vertical Lines on the Graph Indicate Dropped Packets, where the Latency was Recorded as Infinity.

The Netgear WGT634U router processor failed at 130 ± 3 °C. Once the router was removed from high temperature and allowed to cool, however, it began to function normally again. So, irreversible hardware damage did not occur at 130 °C. Visible, irreversible hardware failure occurred at a processor temperature of 140 °C (the ambient temperature inside the oven was 156 °C) when the router's antenna burst, completely negating the node's wireless transmission capabilities.

The router's external plastic case began to melt at a processor temperature of 116 ± 3 °C, lower than the failure temperature of the internal router hardware. Case failure did not affect router operation. Nonetheless, precise router case melting temperature was measured via independent experiment. A K-Type thermocouple was affixed with Scotch® tape to the top plate of the router casing, and the plate was baked inside the oven without the router using the same warm-up routine described in the Methods section. The plastic casing was observed to wilt at 116 ± 3 °C and to bubble at 121 ± 3 °C, the result of which can be seen in Figure 3. This failure temperature is consistent with common commercial plastics such as polycarbonate.[10, 11, 12]

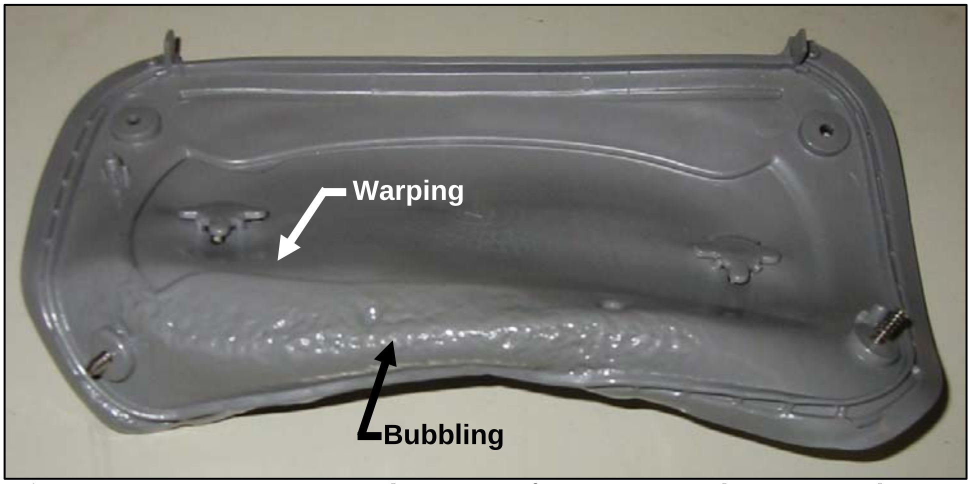

Figure 3. Netgear WGT634U Wireless Router after First Oven Bake to 130 °C Showing Visible Deformation and Bubbling of Plastic Casing from Temperature Exposure.

During the first two experiments, internal router components were protected from direct exposure to thermal radiation by the plastic router case. To determine susceptibility of these components to direct radiation, the experiment was repeated twice with the router case removed. In this later set of experiments, exposed router processor failure temperature was found to be within the experimental error of the temperatures recorded while the processor was protected by the case. These tests confirmed that cessation of router function was attributable to temperature independent of thermal radiation exposure rate.

Discussion

Is direct exposure to high ambient temperature the cause of router node vulnerability observed by Roofnet on hot summer days in Cambridge? No. The highest temperature ever measured in Massachusetts was 42 °C, recorded in Chester and New Bedford in August 1975.[13] Moreover, the steady-state operating temperature of Netgear WGT634U routers exposed to room temperature conditions is about 50 °C, above the hottest temperature recorded in Massachusetts. Will exposure to high ambient temperature cause node failures if a Roofnet network were to be deployed in Denton? No. The highest temperature ever recorded in Texas was 49 °C, in Seymour, in August 1936.[14] Both of these maximum ambient temperatures are significantly lower than the measured router failure temperature, 130 °C.

The observed system shutdown at 130 °C appeared to be not a catastrophic hardware failure but rather a built-in mechanism to shut off the router due to overheating to prevent permanent damage. This conclusion is based on the observed automatic reactivation of the router upon returning it to room temperature from 130 °C. The router returned to proper function after enduring four temperature-induced failures. Netgear would not confirm existence of a temperature shut-off mechanism, claiming this information to be proprietary.[15] Nonetheless, if such a failsafe does exist, disabling it provides one possible route to enable higher-temperature router operation since all critical router components can survive at a processor temperature up to 140 °C without permanent damage.

Importantly, Roofnet routers are not placed outside unprotected in the elements. They are well encased in weather-resistant environmental packages (Figure 4) when mounted outside. Could high ambient temperature coupled with internal router heat generation have caused the environmental casing interiors to reach 130 °C? To show how this failure mode might occur, we applied a conductive heat transfer analysis to a router enclosed in a plastic casing. The following assumptions were used. First, the heat transfer is modeled as a one-dimensional process with heat generated at the router being conducted through a lumped thermal resistance to ambient. Second, the router is dissipating 12 watts; according to the router's power supply, nominal power consumption is 12 watts (12 volts at 1 ampere). Third, the router is running right at its thermal shut-off temperature, 130 °C. Fourth, heat is being dissipated to the hottest possible Massachusetts ambient environment, 42 °C. Finally, the heat transfer coefficient between the outer surface of the package and the ambient environment is infinite (in other words, the outer casing surface temperature is a spatially uniform 42 °C). Under these assumptions, the enclosure in which the router is mounted must present an R value of 7.33 K-m^2/W to induce router thermal shut-off.

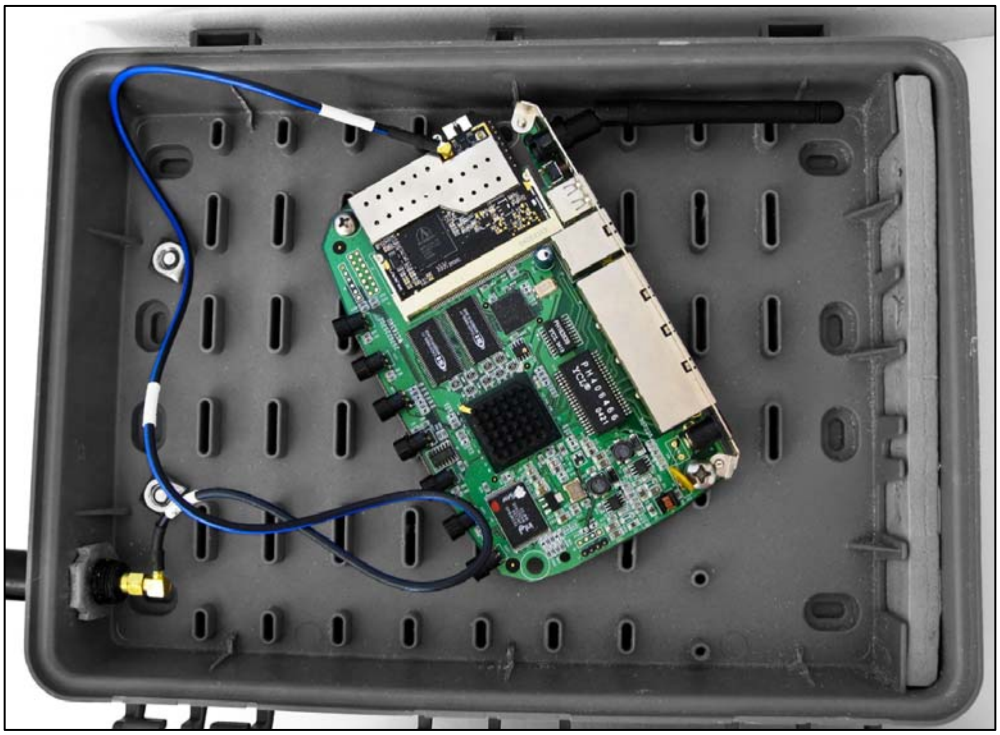

Figure 4. Netgear WGT634U Router Hardware Shown within a Typical Roofnet Weather-Resistant Environmental Package to Provide a Size Comparison. (Image by Lauren Keville used with permission of Kurt Keville, MIT Roofnet.)

By not accounting for the three-dimensional nature of the heat transfer within the environmental enclosure, this analysis gives an upper bound on R for temperature-induced router failure. In addition, the analysis does not account for solar energy absorbed by the enclosure, which would tend to decrease the R needed for thermal failure. Nonetheless, an R value of 7.33 K-m^2/W is too high to be attained within a small environmental enclosure, which becomes evident when comparing this R value to several common insulating materials (Table 1). For example, the common insulating material, low-density 14-centimeter-thick fiberglass bating, presents an R value of merely

3.67 K-m^2/W,[16] only half the required resistance. Air at 86 °C (the mean of 42 °C and 130 °C) has a thermal conductivity of 0.0306 W/m-K,[17] and 22 cm of air in this state is needed to yield an R value of 7.33 K-m^2/W. Initiation of natural convection inside the enclosure with the router at 130 °C and the enclosure surface at 42°C requires an air column less than 1 cm tall. Once natural convective circulation is established, an R value of 7.33 K-m^2/W inside the container cannot be maintained because the air is no longer stagnant.

Table 1. Thermal Conductivity of Selected Insulators and Material Thicknesses to Provide R = 7.33 K-m^2/W, the Thermal Resistance Required for Onset of Temperature-Induced Router Failure.

[redacted]

Ignoring the thermal resistance of the container walls is a reasonable assumption for the heat transfer analysis. If the enclosure were made of a pure, common, environmentally resistant plastic like Nylon (thermal conductivity = 0.24 W/m-K), the enclosure walls would need to be 1.76 meters thick to present an R value of 7.33 K-m^2/W. The actual plastic enclosures used by Roofnet, shown in Figure 4, have walls less than a centimeter thick. Thus, neither the environmental enclosure itself nor the air contained inside provides enough thermal resistance to induce router thermal failure, even under the hottest recorded ambient conditions in Massachusetts (or Texas).

Distance Versus Signal Fidelity

As an additional metric for wide-area router deployment, the maximum viable distance between a node and a receiver was measured by placing an active node at a stationary location in an open field and walking away from it with a Toshiba Satellite P105-S9312 laptop that was actively pinging the node. The terminal distance was defined to be the distance at which the laptop failed to receive 50 percent of the data sent to it. At this rate of packet loss, the effective data transfer rate of the node drops below that of dial-up Internet (less than 56 kilobytes per second) arising from the need to continually re-send lost data packets. A global positioning satellite (GPS) system measured the line-of-sight terminal distance between the node and the laptop at 183 ± 4 meters.

Additionally, a preliminary indoor test determined the extent to which building walls and other interfering bodies affect signal fidelity of the node. Using a method similar to the outdoor experiment, the maximum signal range was found to be severely reduced by interference from the interior and exterior walls of a building. The terminal distance of the node dropped to about 49 ± 4 meters when the laptop was pinging it from within a building.

Conclusions

The Netgear WGT634U router terminal operating distance, where 50 percent of the data sent is not received, is 183 ± 4 meters via line of sight and 49 ± 4 meters from within a building. Netgear WGT634U wireless routers cease to function under high-temperature exposure at 130 ± 3 °C. The router processor shuts off at this temperature, but failure is not catastrophic. Cooling the router to room temperature restores normal function. Irreversible, catastrophic hardware failure occurs at a processor temperature of 140 °C, with the bursting of the router's antenna. However, incidental thermal damage begins at a processor temperature of 116 ± 3 °C when the external router plastic case begins to melt.

Exposure to high ambient temperature alone cannot cause the vulnerability observed by Roofnet on hot summer days in Cambridge, nor will ambient temperature alone preclude municipal broadband networks from being deployed in Denton or any spot in Texas. It is unlikely that an environmental enclosure protecting a router could present high enough thermal resistance to cause the router to reach shut-off temperature. However, a combination of factors including high ambient temperature, high humidity, and absorption of solar radiation by the enclosure might exacerbate router vulnerability. Thus, for deployment in Texas, these enclosures should be redesigned with attention to thermal management to assure that router shut-off temperature threshold is not exceeded.

As with all thermal management solutions, passive design features are always most desirable. Moreover, many Roofnet nodes function in remote locations and are self-powered with no access to grid energy. Thus, active heat mitigation methods, such as fans or refrigeration cycles, are prohibitive from the standpoint of energy conservation. We recommend the following thermal-management-conscious design features for future Roofnet nodes. First, the environmental enclosures should be as small and as close fitting to the active hardware as possible. Small size improves the area-to-volume ratio of the enclosure, enabling better heat dissipation; and close fitting enclosures eliminate the possibility for stagnant air to present a large resistance to heat transfer away from the router. Second, the environmental enclosures should have a reflective exterior finish to reduce solar energy absorption; for example, the enclosures could be manufactured from white plastic. Third, the Netgear WGT634U router processor shut-off temperature should be reprogrammed to 140 °C, the plastic router casing removed, and the antennae placed outside the environmental enclosure. These steps capitalize on the ability of the critical router hardware to function above 140 °C while removing the unneeded plastic casing, which fails at a lower temperature. Furthermore, by placing the antennae outside the enclosure, it can be cooled by the ambient environment while suffering no loss in signal strength due to dampening from the enclosure.

Future Work

Experiments using a range of node temperature and distance combinations will be conducted to determine whether temperature does have any impact on router signal fidelity, especially at the threshold of the terminal distance. A location in the open that has a live 120-volt receptacle is now being prepared to safely power the router furnace apparatus while providing line-of-sight contact with a wireless laptop. Additional environmental variables that could induce router failure, such as high humidity, will also be examined.

Acknowledgments

The authors gratefully acknowledge the donation of Netgear WGT634U routers for this project by Kurt Keville of MIT Roofnet. This work was supported by the Mechanical and Energy Engineering Department and the College of Engineering at the University of North Texas through the Researcher Incubator, a training organization to fast-track undergraduate students into meaningful, early engineering research experiences.

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