The Mesh Network for Refugees and Displaced Persons

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***Abstract*—Today's world is overwhelmed with refugee and displaced persons crises arising from conflicts and natural disasters. Although the international community has made significant progress toward these issues, women and children remain the most vulnerable populations. The development of Wireless Sensor Mesh (WSM) technologies is a paradigm shift for logistics operations, providing continuous visibility, a prerequisite for modern inventory management practices, without expensive, top-of-line infrastructure normally required. WSM can be established rapidly, inexpensively, and without access to dependable power generation or the Internet. Consisting of thousands of low-power wireless devices, WSM creates an autonomous network spreading from fixed gateways no larger than laptops. Revolutionizing major logistical efforts in the defense industry, this technology shows significant promise for use in humanitarian and disaster responses. From personnel accountability and refugee tracking to real-time inventory, WSM provides access to capabilities that would conventionally require huge investment in infrastructure and power. This paper emphasizes the importance of low-infrastructure communication systems like WSM to the management of *logistics* to meet the immediate needs of women and children in refugees' camps. Proper authorities can use this data-agnostic technology to reduce negative impacts of the camps on the host countries, with consideration given to local law and culture.**

Keywords—communication; crisis; displaced persons; humanitarian aid; logistics; protocol; refugees; wireless mesh

I. Introduction

The Humanitarian Charter, established on a concrete foundation of "international treaties and conventions, emphasizes the right of people affected by disaster to life with dignity. It identifies the protection of this right as a quality measure of humanitarian work and one for which humanitarian actors bear responsibilities" [1]. Women and children are at greater vulnerability to overcome the challenges of disaster and conflict circumstances, under which they are exposed to physical violence and cultural barriers preventing them from receiving the support they are entitled to [2]. This is not an obscure issue when looking at disasters, whether natural or manmade conflicts, through the lens of humanitarian practitioners, who recognize the immediate needs and communicate these needs and the flow of displaced persons (DPs) throughout certain tracks to obtain supplies and relief on time. However, after decades of hard work that the international community does to relieve distress and hardship, there is still a lot of work to do. This paper highlights three major challenges that almost every humanitarian crisis faces: (1) vulnerability of women and children, (2) communications and personnel accountability, and (3) logistics and security. A reliable, easy-to-deploy, and cost-effective communication system, such as the Wireless Sensor Mesh (WSM) described herein, could ensure the timely flow of information to increase the ability of humanitarian organizations to respond in times of disaster and ultimately save lives.

II. Wireless Sensor Mesh Overview

It is important to note that most refugee and DP crises happen in developing countries, where the lack of infrastructure hinders the process to respond and remediate the hardship. Therefore, a communication system that can function effectively, efficiently, and economically in austere environments is vital. A new WSM protocol has the potential to provide reliable and inexpensive communications in harsh refugee camps and along austere logistics supply chains. This protocol, known as mist® [3], is a self-managing network of independent, battery-powered nodes operating over the 2.4 GHz Instrument, Science, and Medical (ISM) band using commercial chips based on the IEEE 802.15.4 standard [4]. The protocol enables communication between the nodes without the need for pre-existing communications infrastructure or centralized control [5]. The protocol was developed to support logistics processes in both developed and remote locations while providing much-needed security, as logistics processes are often subject to theft and tampering. The protocol is a new capability for the Internet of Things, and having been developed for tracking and monitoring items and shipments as they flow through logistics processes, it was designed for ultra-low-power operation to enable long battery life while maintaining reliable connectivity in dynamic mesh topologies. The authors' organization has been involved in mist® development and deployments since 2007, and mist® is now available for licensing from RSAE Labs.

The need for reliable communications for public safety in humanitarian crises is well documented [6], and deployable Wi-Fi–based mesh networks can provide reliable connectivity between a limited number of network nodes at any location that is involved in humanitarian relief but is typically limited to providing TCP/IP networking to buildings, shelters, and tents where relief workers are present. The cost and power requirements of such nodes do not support providing communications for individual refugees and DPs. In the logistics market, Wi-Fi technologies are rarely used for tracking items and containers in logistics processes. Battery life is too short, and Wi-Fi meshes cannot support mesh networks with thousands of nodes in one location.

The IEEE standard 802.15.4 was developed to enable low-power mesh networking for a variety of sensor applications, with its use for building automation being the most significant market and ZigBee [7] the most widely recognized application. Over the years, a number of companies and organizations have attempted to use IEEE 802.15.4–based technologies to track items and containers through logistics processes [8], but with little market success.

The concept proposed here is to deploy sensor mesh gateways to provide connectivity in one of three ways—at Wi-Fi–based TCP/IP nodes, plugged into individual PCs by using a mesh-equipped USB dongle to provide local visibility without any communications infrastructure, or connected to Iridium Short Burst Data (SBD) satellite modems to provide connectivity of the sensor mesh network to the Internet from anywhere in the world. Fig. 1 illustrates the proposed network topology. Because of the low-cost and low-power consumption of IEEE 802.15.4–based devices, the potential exists to apply WSM nodes to individual people, to pallets of supplies, and to equipment that requires monitoring using inexpensive sensors. This capability has not been demonstrated to date because most battery-powered WSM protocols do not support battery-powered mesh routing nodes. Typically, in ZigBee and ZigBee-like protocols, the routing nodes are line-powered, and only the "leaf" nodes are battery-powered. But line-powered nodes make them incapable of movement in dynamic processes, and companies attempting to use 802.15.4-based technologies for dynamic processes require frequent recharging of routing nodes, or they end up deploying a significant quantity of stationary, powered nodes to enable all mesh routing, resulting in substantial costs for this additional layer of communications "infrastructure."

The concept described here is now possible because unlike other wireless sensor mesh network protocols, all nodes in a mist® mesh network are full-routing nodes when operating on battery power without a power penalty and at average power levels well under one milliwatt while supporting a radio range of 200 meters. The innovations in the mist® protocol's routing algorithm enables greatly reduced routing complexity and therefore lower power consumption versus mesh population [9], as illustrated in Fig. 2. This new capability enables expansive networks, in one instance reliably supporting logistics processes involving several thousand mesh nodes distributed over an area exceeding four square kilometers.

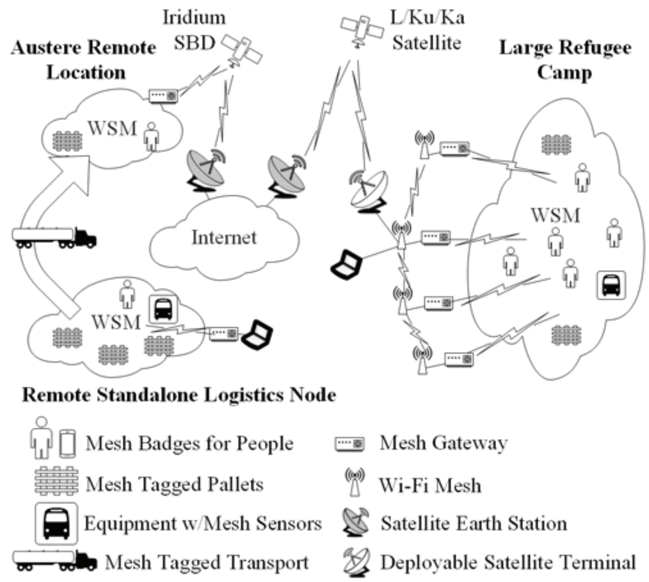

Fig. 1. Austere network topologies with WSM.

III. • Vulnerability of Women and Children

Understanding the vulnerability of women and children during crises is important. The United Nations High Commissioner for Refugees and other local and international organizations have conducted swift assessments of the Syrian refugees in Lebanon in the fall of 2013. They found that women and children are the most vulnerable groups due to increases in various types of violence and lack of safe access to services [10]. In addition, and from the firsthand experience of one of the authors during the Iraq War in 2003, the phenomenon of DPs has widely spread throughout the country, leading to a significant increase in gender-based violence. Thousands of families were forced to leave their homes, left out in remote and desert areas with no supplies. That scene of people marching hundreds of miles fleeing bombs, hurricanes, earthquakes, landslides, and the like stays in minds and urges the humanitarian community to better address such human hardship.

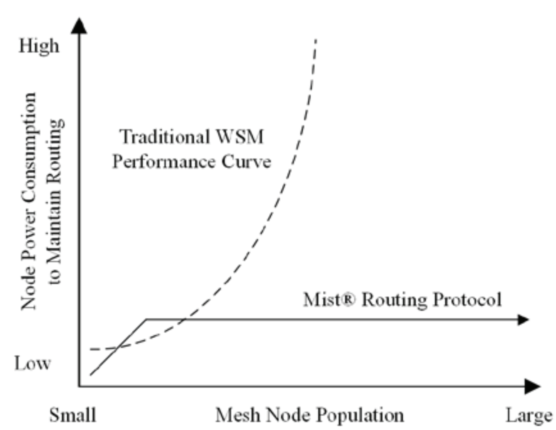

Fig. 2. Ad hoc sensor mesh routing challenge.

The current large-scale humanitarian disaster is the refugees and DPs in the Middle East. It has been addressed by Amnesty International, which reported "that the risk of rape for women living in camps has increased dramatically…" [11]. A similar issue faces the Syrian refugees in the Middle East, specifically in Jordan, where 80% of this group comprises women and children who are at a great risk of sexual, physical, and psychological abuse, yet they have limited opportunity to access safe spaces or social services [12]. In an assessment conducted by the Women's Refugee Commission earlier this year, the findings show that transit centers for refugees are not proper to provide protection to women and girls; "lack of information leaves women and girls vulnerable to smugglers and other opportunists" [13].

Nevertheless, it is similar to Haiti, Somalia, Rwanda, Kosovo, and many other places in the world—women and children are at the greatest risk. For example, it is notable that women and children are involuntarily required to stand for hours in haphazard lines waiting for supplies and then must carry heavy loads of distributed drinkable water and food. If they fail, they could be subject to physical violence for not bringing necessary aid supplies to their families. In addition, refugees face resentment in some host nations and communities as being viewed as "materially privileged, since they are receiving aid" [14]. Such environments put refugees and their families at a greater hardship. Haiti is another example, as some local Haitian aid workers expressed their firsthand knowledge about domestic violence and sexual assaults against displaced women in the camps and how it is a challenge for them to get the information from the victims, report it properly, and actually do something about it. As corroborated by a researcher in the women's rights division at Human Rights Watch, "The camps for people displaced by the earthquake, where I spent months in 2010 and 2011 documenting sexual violence and inaccessibility of justice and services, are the site of many attacks" [15]. Because Haitian law discriminates between domestic violence against minors and adults, the latter is not classified as a crime [15].

By deploying mist® devices to individuals in the format of an identification badge with an integral panic button, the mesh offers a low-cost, low-power, bi-directional communications capability, with minimal infrastructure, to provide location reporting, information sharing, sensor data collection, emergency alerting, and emergency response. A modest number of mist® gateways that communicate all mesh-collected data to traditional TCP/IP networks would enable the extension of critical safety communications to individual refugees at significantly lower cost than other communication technologies. The panic button on personnel badges could leverage mist®'s powerful routing features [16] to notify a security center and deployed security personnel, and it could even notify other DPs in the immediate vicinity to effect a "neighborhood watch"–like emergency notification network. Cultural sensitivities would need to be evaluated in these use cases, but the potential exists to empower DPs, especially those most at risk, to establish local communities of interest to ward off at least some of the threats to DP safety.

IV. Communication and Personnel Accountability

The second aspect of addressing refugee and DP crises is the communication and accountability of the aid actors and stakeholders, including the host communities. It is very critical to the relief missions that all humanitarian aid and relief responders work in harmony and collaboration [17]. Examples are countless in that regard, in which the cause of key challenges are simply a lack of understanding who the key players are in responding to crises and what information is being communicated to them. These challenges could cause an impact on logistics. For instance, during post-evacuation shelter preparations of Hurricane Katrina in 2005, the Red Cross was tasked with housing and sheltering evacuees and relied on the Federal Emergency Management Agency (FEMA) for information on the number and timing of evacuees, "but there appeared to be no correlation between the information communicated by FEMA and what actually happened" [18]. Scheduled arrivals were canceled at the last minute, negating the preparations that took place, while in other instances, large numbers of evacuees would arrive without advance notice to places where no preparation had occurred.

The issue seems to be reflected in the lack of proper interagency communication and the understanding of who is doing what. As described in a report to Congress [19], a persistent challenge for aid and relief operations is that the communication between government agencies and aid stakeholders is inadequate. Information and the time to gather it is critical in such circumstances. As highlighted in a 2005 study of the challenges that have an impact on the effectiveness of humanitarian aid organizations' operations, the lack of proper investments in information and communication systems (ICS) that are customized to their particular needs is a significant challenge: "Helping [non-governmental organizations] overcome the many challenges to effective use of ICS is a critical component of this vital support" [20].

However, in context of conflicts and disaster response, when communication infrastructure is not available or not reliable, the use of technology that is needed to maintain the "minimal services are mostly expensive satellite phones or specialized point to point radio communication systems" [21]. A wireless mesh network has diverse requirements that include "low up-front cost, easy network maintenance, robustness, reliable service coverage, etc." [22]. The establishment of an effective communication system to manage refugees and DPs is vital to promote transparency and to ensure accountability by "provid[ing] accessible and timely information to affected populations on organizational procedures, structures, and processes…to make informed decisions…" [23].

By distributing WSM devices to DPs and aid workers, the ability to track people in near-real time would support a more precise and timely distribution of relief efforts. With an e-ink display [24], the same devices could be used to display messages broadcast to the refugees and/or aid workers over the mesh that could help direct them to the proper location to receive aid and supplies, along with communicating emergency notifications. mist®'s encrypted messaging and multicast routing capabilities would enable messages to be distributed to select individuals as appropriate, and even enable transmission of encrypted messages to individuals. Encryption and selective delivery are important as a means of ensuring data confidentiality and preventing bad actors from accessing or manipulating the mesh network for their purposes.

V. Logistics and Security

Refugees and DPs typically have an urgent need for necessary supplies like shelters, water, and food. The logistics and security of staff and goods are key intertwined factors to saving peoples' lives. During chaotic situations like disasters and conflicts, the humanitarian supplies could be captured and attacked by rebels, criminals, and spoilers of conflicts to redirect humanitarian supplies to meet their own needs, preventing the supplies from reaching refugees and DPs [25].

The safety and security of aid workers has become a huge concern of humanitarian and relief organizations, especially in conflict zones where the logistics of aid distribution is at high risk [26]. The year 2013 brought a new record of violence against aid personnel, mostly in the form of attacks while carrying on logistical operations of aid distribution [27]. Therefore, establishing a secure communication system like the mesh to track personnel and supplies with real-time information would be vital for secure and tailored logistics of humanitarian needs. The "right-sizing" of logistics packages will increase aid worker productivity and free up aid personnel to work on other tasks. These improvements in logistics distribution processes are only possible if the WSM network can support large mesh populations that are in motion and mist® can satisfy the requirement.

The ability of mist® to track the location and status of materiel in transit, providing 100% visibility of supplies within the logistics system, is a critical capability. Even when lacking any communication infrastructure, mist® gateways using iridium satellite modems have demonstrated global visibility at very low-unit costs and without any human action. Single-use mesh tags can be placed on palletized goods prior to shipment, and USB-powered mesh gateway dongles connected to laptop computers at nodal logistics points can record the arrival and departure of pallets and provide near-real-time local inventory management without any fixed communications infrastructure or satellite communications.

Some users of mist® have already demonstrated the ability to collect sensor data from systems often deployed to humanitarian missions, to include monitoring electric generators, environmental control units, refrigeration systems, water purification systems, vehicles for faults and usage, and fuel levels in vehicles and supply tanks (stationary or on trucks.) The same sensor nodes also support the dual purpose of tracking the equipment en route and maintaining inventory.

Mist® devices could also be deployed with motion and other sensors to provide perimeter security to locations that require protection. Because all of these capabilities utilize the same mesh network, mist® has the potential to drastically reduce the infrastructure required to monitor equipment deployed to humanitarian crises and greatly simplify the technical support requirements, compared with other sensor communications technologies.

VI. Development of the mist® Protocol

The impetus to develop a new WSM protocol was the recognition of several inter-related limiting factors governing WSM networks: scalability, message reliability as mesh nodes move around, message latency, and power consumption. To date, the majority of WSM protocols have been designed for the building automation and process control markets, supporting low-latency applications and generally small, static mesh topologies. By focusing on logistics applications in which process latencies are often in the tens of seconds instead of the fractions of a second, as is common to protocols like ZigBee [28], the mist® development team was able to trade message latency for a number of protocol features that satisfy key logistics requirements, to include ad hoc mesh formation that continually works to optimize routing in dynamic environments, large mesh node–to-gateway ratios (over 2,000:1 in many instances), very low power consumption (less than a milliwatt of average power while maintaining continuous network connectivity), and FIPS 140–certified security on every node, which traditionally has been viewed as an added burden to network routing and power consumption [29].

A key capability unique to mist® is the "variable speed" nature of the protocol. Early in mist® development, the team recognized that mesh node density had a significant impact on mesh join times, latency, and battery life. At the same time, the trend lines of mesh performance are often orthogonal to the characteristics of logistics processes. Fig. 3 illustrates one of the challenges of applying WSM technologies to logistics processes. Because of the low power requirement, WSM nodes used in logistics processes need to operate on very low duty cycles, reducing the opportunity for network joining processes to succeed. As a result, small mesh populations have slower join times and take longer to optimize, yet logistics nodes with small populations are often the most dynamic. Therefore, the team developed the mesh protocol to be variable speed, enabling mesh operators to opt for either lower latency at the expense of reduced battery life or longer battery life in exchange for greater latency [30]. These settings can be different at different locations or adjusted for different processes, applications, and population densities. This capability is unique in the WSM market, especially the ability to vary latency by two orders of magnitude and node battery life by over one order of magnitude.

Fig 3 illustrates small mesh populations that may have only 3 to 5 mesh nodes within their radio's range of each other (for example, when only one truck load of mesh-tagged pallets of relief supplies arrive at a forward distribution location). Conversely, large populations may have hundreds of mesh-tagged items within radio range of each other (for instance, at the pier of an ocean port where ships are being unloaded). With a fixed set of mesh settings for the join process and periodic communication between mesh node pairs, the latency of the first report for a newly arriving logistics item may be ten seconds in a large population but minutes in a small population (see the dashed line in Fig 3). By implementing the variable speed feature, the mesh's performance can more closely approximate Fig. 3's solid line, which better matches logistics processes, resulting in significantly longer battery life. As the protocol development advanced and tests were conducted, the protocol feature set was expanded so that the variable speed settings of the mesh can be self-determined within the mesh on the basis of local conditions to further maximize battery life or reduce latency, per the owning organization's priorities at each location.

Because long battery life is essential for economical communications to individual mesh nodes used in logistics processes, mist® is a very low bandwidth network compared with TCP/IP-based technologies. This means that the bandwidth limit for the mesh equals the data throughput of the mesh radio chip at the mesh gateway, and the current maximum is approximately one megabyte per hour, although new chips will increase this rate.

But even at this limited data rate, mist® is adequate for a significant volume of periodic messages and even for data packets the size of text messages often used by cell phones. Just as Open Garden's FireChat and Jott's AirChat have enabled text messaging between cell phones without requiring network infrastructure [31], mist® can accomplish the same task and topology, but at a fraction of the power consumption of cell phone–based mesh networks used for text messaging.

Although latency is affected by the number of hops required to communicate between two nodes, the routing topology of a mist® network means that latency often increases slowly as the number of nodes increases. The mist® protocol also features continuous channel hopping, which makes it very resistant to radio interference from other devices operating in the 2.4 GHz ISM band, further increasing message reliability. In addition, most contemporary devices consider battery life in terms of hours of operation, yet a mist® device with a lithium coin cell can operate for over a month on one cell, and the battery of a typical cell phone would maintain continuous mist® communications for over a year without recharging. In an austere environment, battery recharge may be impossible or logistically difficult, so mist's low energy consumption will help to reduce operational costs and logistical challenges. As predicted by Moore's Law, the mist® development team has already benefited from longer battery life as new chips enter manufacturing, and that trend should continue in the future, further reducing the cost of mist® devices.

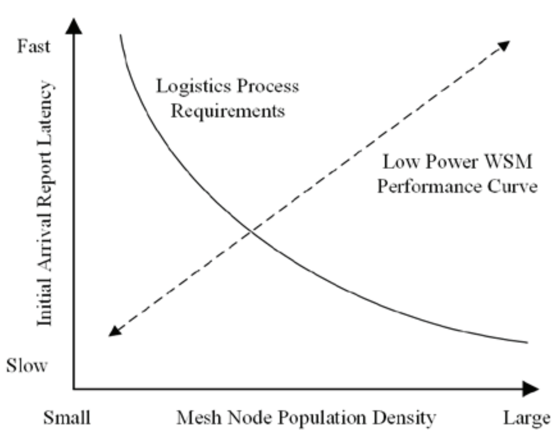

Fig. 3. Ad hoc sensor mesh speed challenge.

The security of mesh-collected data and the ability to deny "bad-actors" access to the network is improved by implementing a strong security posture on every mesh device. In 2013, the mist® development team secured FIPS 140 certification of a Texas Instruments IEEE 802.15.4 "System on a Chip" (SoC) when loaded with the mist® firmware [32]. As a NIST-certified crypto-module, the single chip is the crypto-boundary, and it includes the main processor, radio, AES encryption co-processor, and memory; the module's functionality includes the physical, link, network, and transport layers of the mesh network protocol stack. Mist® is the only IEEE 802.15.4–based ad hoc sensor mesh featuring battery-powered routing nodes to attain crypto-module certification. This capability would make it very difficult for criminal elements to hijack the mesh, generate spurious panic button messages, and broadcast incorrect information to e-ink–capable devices.

Table I summarizes the high-level functional requirements for a WSM to support logistics processes on the basis of extensive supply chain management experience and the lessons learned from developing a WSM protocol for logistics. Those familiar with WSM protocols will recognize that these are a superset of requirements when compared with most prior WSM protocol development efforts.

TABLE I. REQUIREMENTS FOR LOGISTICS WSM

Requirement	Basis
All nodes must "advertise" the mesh and route traffic to and from other mesh nodes	In a dynamic topology, some nodes are in motion, and the presence of "leaf" nodes reduces the ability of the mesh to heal and admit new members as nodes move through logistics processes.
Reliable message delivery in dynamic mesh topologies	Technologies that cannot provide reliable and accurate data typically fail to gain market acceptance in logistics processes because they do not enable significant operational savings.
Minimum assured battery life	Nodes cannot suffer from reduced battery life just because they become the child of a gateway. Assured battery life ensures that a mesh node can track an item until it has completed its logistics journey.
The network must be bi-directional	The ability to transmit information onto a mesh node used in logistics processes allows shipment-specific information to be retrieved by handheld devices at remote locations that lack Internet connectivity, a common occurrence for austere logistics operations.
Automated least-cost routing	Mesh gateways may use satellite, cellular, or TCP/IP networks for connecting a mesh to the Internet. The communications costs vary significantly. When mesh nodes move through logistics processes, they should automatically shift to the lowest cost gateway to minimize communication costs in austere areas.
Variable-speed mesh	Logistics processes have very different population sizes and time constants. Power consumption of battery-powered devices is a function of network speed. Support variable network speed to maximize battery life.

Requirement	Basis
High mesh “tag”–to-gateway ratios—at least 1000:1	To be cost-effective, deploying and operating mesh gateways needs to be a small portion of total cost of ownership. This can be accomplished by minimizing gateway installation costs and the total number of gateways required. For very large mesh populations, the ability of multiple gateways to interoperate without human action also reduces total operating costs.
Security, with FIPS-certified encryption	Many logistics processes involve multiple stakeholders and actors. The inability to secure logistics data can lead to additional theft and revelation of proprietary data and processes.

From the perspective of technical innovation, by trading message latency for a critical set of capabilities necessary for ad hoc, fully autonomous, and low-power sensor mesh communications, the mist® protocol has demonstrated a new paradigm shift in wireless communications. Just as the routing capabilities of TCP/IP networks represent a paradigm shift by displacing much of the circuit-based switching previously used in telecommunications, mist® has the potential for a similar paradigm shift in sensor networks that do not require low latency. In this case, because only a small portion of the significant number of communication paths available in a large mesh network need to have reliable RF connections, the radios and antennas used do not require the expensive configurations normally associated with at least one end of reliable point-to-point wireless systems, such as cell phone towers. Instead, because the latest commercial-of-the-shelf IEEE 802.15.4 SoC chips [33] can now support a feature-rich wireless mesh network routing protocol like mist®, inexpensive radios and antennas can be used on all devices, significantly reducing manufacturing and deployment costs. In addition, reliable communications can still be provided to nodes that find themselves in inopportune locations and antenna orientations, as they only need to communicate with one other node in the mesh to gain communication over the mesh to the Internet. This is a significant paradigm shift in wireless communication that mist® is just beginning to demonstrate.

VII. Conclusion

We live in an interconnected world, in which a crisis in one country can have a negative impact on other countries. The international community has been focusing for decades on promoting humanitarian and relief assistance for refugees and DPs; however, women and children are still the most susceptible to violence and hardship. In other words, the refugee camps and DPs witness an increased rate of domestic violence and sexual assaults, yet these events are not reported and documented properly. In addition, during chaotic circumstances such as conflict and natural disasters, there appears to be an issue of poor communication of accurate data to and between all stakeholders, in turn affecting the flow of real-time information and personnel accountability. A reliable and agile wireless mesh technology that can inexpensively deliver communication capabilities for people and logistics in austere environments is the most suitable method to facilitate safe humanitarian operations efficiently and promptly, with quality data and streamlined flow of real-time information.

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