Rainfall field reconstruction using rain attenuation of microwave mesh networks

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ABSTRACT

Rainfall detection using commercial communication links can complement the existing weather satellite and radar system. Using the rain attenuation data from these networks, the paper proposes a new method of reconstructing the rainfall field through a compressed-sensing based algorithm. Compressed sensing is a new algorithm that can reconstruct a sparse signal from a relatively small number of measurements. System configurations of two links and three links crossing a single area are studied and the detection accuracies for rain location and attenuation level are evaluated. The proposed method is also tested for different climate and weather patterns. The results show that the proposed method has good location detection accuracy, and the rain intensity was reconstructed as well. The proposed detection system and reconstruction method can greatly benefit the tropical countries that experience frequent rains but do not have enough resources for weather forecasting and detection of possible disaster-inducing rain events.

Keywords: Rain Attenuation, Microwave Mesh Network, Compressed Sensing Algorithm

1. INTRODUCTION

Tropics refer to the part of the world that is within the 23° latitude from the equator and nearly two-thirds of all rain events happen in this region. Economically speaking, most tropical countries are considered developing countries and have less rainfall sensors than one would find in a developed country. Most typhoons also develop in the tropical region. These typhoons form and move faster and require more sophisticated forecasting, something that is hard to do in developing countries. Because of the frequency and intensity of rainfall events, tropical countries are also more susceptible to rain-induced disasters like landslides and flash floods.

The climate in tropical countries is divided into two seasons rainy and dry although it is not unusual for these countries to experience rain all throughout the year, even during the summer season. Also, rain events do not necessarily have to be associated with large-scale phenomena like typhoons. In fact, summer rains or rain some time during a fair weather day is normal in tropical countries. There are several known characteristics of tropical rain as compared to mid-latitude or temperate region rain. Tropical rains not associated with typhoons can still be very intense over a small area and can reach rain rates of more than 200 mm/hr at a time. The cell size of these events can be from sub-kilometer to a few kilometers. They can also last from several minutes to a few hours. Due to these characteristics, tropical rains can trigger disasters like flash floods and landslides. Tropical rains can dump a huge amount of rain in a short period of time, causing the swelling of rivers and drainages. The intense localized rain can also produce enough force that can drive down the soil and trigger landslides.

There are several ways of detecting and forecasting tropical rain. The most common method is through the use of weather satellites and radars. Meteorological satellites have the advantages of covering the ocean areas for improved forecasting, and they can also see the start and development of typhoons for improved typhoon warning services. Long-term satellite data are also used to understand the weather and climate patterns for better forecasting. Weather radars, on the other hand, are used to detect the typhoon as it approaches. Radars are capable of calculating the motion of the rain clouds, the type of precipitation (rain, snow, etc.), and the intensity. Weather radar data are important in determining potential severe weather patterns. A disadvantage of satellites and radars, however, is that they are not suitable for ground level rain estimates. The ground level rain data is important to calculate the possible runoff that can cause flash floods and landslides.

One way to get the ground level rain is through the use of local weather stations. These weather stations usually consist of a set of instruments to measure different weather parameters like rain, temperature, pressure, wind speed and direction, and humidity. They take real-time measurements of weather events happening in the specific location where they are deployed. The data from these stations are used to verify the forecasts made using the satellites and radars, and to monitor the current weather conditions in a specific area. A good deployment of weather stations is through a mesonet, which is a network of sensors used to observe weather phenomena in the

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Manuscript received on December 15, 2012 ; revised on January 5, 2013.
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scale of 5 kilometers to around 1000 kilometers. The distinguishing feature of a mesonet is the station density and temporal resolution. The spatial spread out of weather stations can be from 2 to 40 kilometers, while the temporal resolution is every 1 to 15 minutes. However, mesonet deployment can be very expensive as it depends on the number of stations available, and only some developed countries have permanent mesonet systems. Normally, most weather stations used by other government entities, private companies, and individuals are deployed in the scale of one in every tens of square kilometers. For the purposes of detecting localized tropical rain, which happens in the sub-kilometer scale, the weather stations normally deployed few and far in between are inadequate.

A novel method of detecting rain using microwave links has been proposed in the last few years. Signal attenuation due to rain is the main problem of wireless communication networks above 10 GHz. In these frequency bands, the radio frequency signal is absorbed mainly by raindrops with the same drop size as the wavelength of the signal. There are several advantages to using microwave links as rain sensors. First, the microwave links are already deployed for commercial communication purposes, and real-time attenuation data is measured as part of the monitoring and maintenance of these links. This means that not much overhead cost is needed to build a rain sensor using the same network. Second, the spatial and temporal resolutions are greatly improved with the use of microwave links. The effective coverage area of the links fit the size of the rain clouds and the observations are made continuously, sometimes in per second resolution. Lastly, deployed microwave links are designed to tolerate rain by a certain fade margin. Within this margin, the received signal level (RSL) varies with respect to external disturbances, which is mostly rainfall. As long as the RSL does not reach the minimum receiving level of the antenna, the system can record the attenuation due to rain at any given time. The attenuation and rain rate relationship is given by an empirical power-law equation commonly used for link design [1].

Prediction methods and design models like ITU-R P.530 and the Global Crane Model are usually used in designing microwave networks to withstand rain attenuation. Microwave links experience a certain amount of signal absorption depending on the intensity of a rain event but they can still function normally as a communication channel. This change in RSL measured over a certain distance can be used to infer the rainfall rate within the signal path. Matzler, et al., showed the potential of using directional transmission links to derive the rain rate at a high time resolution and in near-real time [2].

Recent research has shifted from determining the rainfall rate from one link to reconstructing the rainfall field using the attenuation data from several links. Goldshtein, et al., showed how commercial telecommunication links in Israel can be used for rain rate estimation and for generating 2-D rain maps by using a modified weighted least squares algorithm [3]. This paper proposes a compressed sensing-based method for detecting the rainfall location and intensity from the attenuation data of microwave mesh networks. Compressed sensing is a new technique that can reconstruct a signal or image using a limited number of measurements [4]. This is useful for rain detection because there are only a limited number of attenuation measurements over an area of several kilometers. Another characteristic of tropical rain is that the rain rate in surrounding areas is usually very much smaller than that in the affected area. This makes the data sparse, which is another requirement for compressed sensing [5].

This paper is organized as follows. Section 2 will discuss more on the method of detecting rainfall using the microwave mesh network signal attenuation while Section 3 will expound more on the concept of compressed sensing. Section 4 will describe the system model used in the network simulation and the explanation for the rainfall field reconstruction and simulation results. We conclude the discussion in Section 5.

2. RAINFALL DETECTION USING MICROWAVE ATTENUATION

Wireless network deployment has gone up in the last decade all over the world with the development of new technologies and availability of wider markets. People are becoming more mobile and the wireless networks provide the mobility and accessibility that this fast-paced generation demands. Microwave links are the backbone of these networks but these frequency bands are very susceptible to rain. Rain fades start to become a concern at around 5 GHz and is very evident at frequencies above 10 GHz [6]. Rain is an important factor in determining the link availability and reliability, and a good microwave design relies heavily on the rain statistics of a particular deployment area.

Link designers take note of the effects of rain on microwave signals mainly for the quality of service. However, studies in the recent years have shown that the same RSL attenuation data can be used as an indicator of the intensity of the rain along the path of the link [7-8]. Many studies suggested the use of wireless communication networks for environmental monitoring and used the observations to supplement the data provided by conventional rain sensors [9-10]. A study by Messer, et al [11], used the wireless communication networks of Israel to monitor and reconstruct the rain fields. Path-averaged rainfall from wireless links has also been the topic of several studies. In a paper by Rahimi, et al [12], they made use of two microwave links from different frequency bands. The difference in attenuation between the two links was used for rain attenuation, and the use of two frequencies resulted in a relatively more linear relationship between attenuation and rain rate, as compared to using only one frequency and then using the exponential power law model to get the rain rate. Meanwhile, Berne and Uijlenhoet showed that the path-averaged rainfall estimation using microwave links has an uncertainty due to the spatial variability of rainfall [13]. This finding is more obvious with tropical rain because individual rain events can have a size as small as a few hundred meters to several kilometers. The movement of rainclouds is also fast such that each event can be passing through the links in only a short period of time.

Microwave signal attenuation can be caused by several factors. These are the long-distance propagation free-space loss, attenuation due to trees, and atmospheric attenuation due to rain and other types of precipitation. The first two are taken into account during the design phase of the link setup and are often addressed by selecting the proper link distance, antenna location and polarization, and transmit power among others. A rain fade margin is also incorporated into the calculations to account for rain events that can significantly degrade the link quality. There are several radio propagation models developed to calculate the predicted attenuation due to rain. The ITU-R P.838 recommendation [14] gives the specific attenuation model for rain as

$$\gamma = kR^{\alpha}. \tag{1}$$

In this equation, γ is the specific attenuation due to rain in dB/km and R is the rain rate in mm/hr. Constants for the k and α coefficients are developed from scattering calculations and differ in value for different frequencies (1 to 1000 GHz) and polarization (horizontal or vertical). The values for these constants are already given in the recommendation. The link attenuation can be calculated by getting the sum of the specific attenuations in a given link path.

The horizontal profile of a rain event has large spatial variation, with most of the rainwater pouring in the center of the event and gradually dissipates toward the edges. The vertical profile is also variable with different cloud heights, but microwave detection of rain is considered near-ground sensing and is not affected by this variation. The rainfall rate as it passes through the signal is the same as the rate as it falls to the ground. Since microwave links can detect the presence of rain along the link, it is also possible to infer the rain location from the simultaneous attenuation in mesh network. One way to do this is shown in Figure 1. Suppose that there are three crisscrossing microwave links in a 5 km by 5 km area. In a rain event, any of the three links can experience signal attenuation. The location of the rain can be inferred by looking at the path of the link that experienced signal degradation. If two or more links get attenuated at the same time then it is probable that there is a rain cloud large enough to affect several links. The accuracy in detection also increases when the number of links crossing a certain area increases. In the figure, detecting rainfall in Area B will be very accurate when all three links are attenuated at the same time. The area where all three links intersect will always have higher detection accuracy than the other areas where only one link is present. The movement of the rain cloud can also be inferred from looking at the time series attenuation of each link and will have more accuracy when there is available data on wind direction. Given the attenuation of the mesh network, the specific attenuation can be derived using a method called compressed sensing, which is discussed in the next section. Finally, the rainfall rate in an area can be derived from the specific attenuation using Eq. 1.

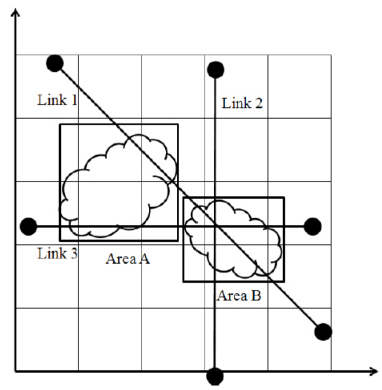


Fig.1: *Determining Rain Location.*

3. COMPRESSED SENSING ALGORITHM

The idea of compressed sensing was introduced in [15] and [16] to avoid sampling the part of the signal that will only be lost in compression. The sparse image can be accurately reconstructed from lesser samples than traditional methods use. It is commonly applied to areas such as image processing and channel state estimation. It is specifically useful when the data to be reconstructed is sparse, i.e. mostly negligibly small or zero.

A linear measurement model is commonly given by

$$\mathbf{y} = \mathbf{A}\mathbf{x} \tag{2}$$

where y is an m-vector of measurements, $x = (x_1, x_2, \ldots, x_n)^T$ is the desired sparse unknown n-vector, and $A = (A_{1,1}, A_{1,2}, \ldots, A_{m,n})$ is an $m \times n$ known measurement matrix. In this particular application, the number of measurements is much less than the dimension of the signal, making it an underdetermined system where there are fewer equations than unknown. An underdetermined system can be solved using non-linear regularization. If x is determined to have a unique sparse solution, then compressed sensing can be applied. Compressed sensing makes use of l_1-norm minimization which can be solved using linear programming. The reconstruction is given by

$$\hat{\mathbf{x}} = \underset{x}{\operatorname{argmin}} \|\mathbf{x}\|_1 \quad (3)$$
$$\text{subject to } \mathbf{y} = \mathbf{A}\mathbf{x}$$

To apply compressed sensing for rain detection, $\mathbf{y}$ is the RSL attenuation measurement for each link in the mesh network and $\mathbf{x}$ is the unknown or the specific attenuation in a 1 sq. km area. The measurement matrix $\mathbf{A}$ corresponds to the detection area and is defined by the presence or absence of microwave links in a specific location. In the example in Fig.1, there are only 3 links but there are 25 unknown specific attenuations per square kilometer. The spatial diversity of tropical rain is such that most of the time, not the whole area will be covered with rain, making the unknown sparse. Hence, the idea of compressed sensing reconstruction can be applied in the proposed rain detection method. The system configuration and network simulation implementing this algorithm in a mesh network is shown in the next section.

4. SYSTEM CONFIGURATION

To simulate a microwave mesh network and its attenuation due to rain, a 5 km by 5 km area was chosen and a specific number of links was placed on it. The rain rate data used is from Japan Meteorological Agencys radar data, with a resolution of 1 km by 1 km for every 5 minutes. For this research, the rain data is from July 2009 to July 2010 to account for all the seasonal changes. For every instance that the 25 sq. km. area has rain of any amount, the 25 specific attenuation values were computed using (1). In this study, 25 GHz vertically polarized links were used, and the value of k is 0.1533 and the value of α is 0.9491 [17]. The rain rate is given in mm/hr. The link attenuation can then be computed by adding the specific attenuations along the path of the link.

Two types of simulation were done. First is for the comparison of detection accuracy when using 2 or 3 links crossing a single area, and the next is for the comparison of detection accuracy for 3 different areas with different weather patterns.

4.1 Two or Three Links Crossing an Area

Figure 2 shows the microwave network placements in a 25 square kilometer area.

For Fig. 2a, each area is defined by 2 crossing links and there are 10 links in total. Initially, the values for x_1 to x_{25} is calculated using (1) and the link attenuation is calculated from the specific attenuations in the following manner:

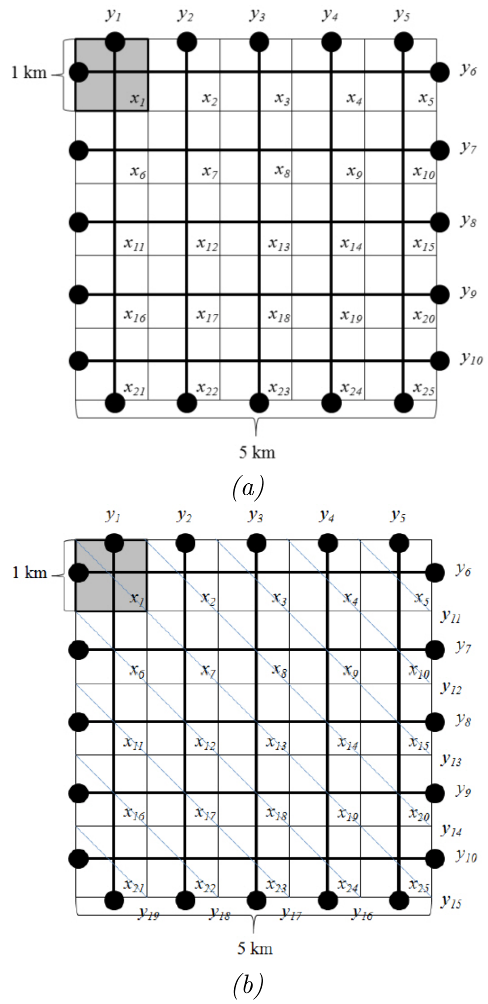
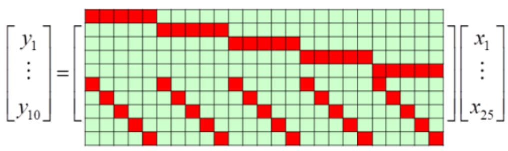


Fig.2: *Microwave Mesh Network.*



(4)

Here, the measurement matrix defines where the links are located, where the value of red is 1 and green is 0. Therefore, the link attenuation y is the sum of the specific attenuations in areas where that link passed through. These link attenuation values were then used in the compressed sensing-based reconstruction of the specific attenuation. Eq. 3 is a linear programming problem that can be solved through Matlab. In addition to the given constraints, a set of lower and upper bounds on x were also defined as follows:

$$0 \leq x \leq 25 \quad (5)$$

These boundaries were chosen because a microwave link cannot record a negative attenuation and also attenuation beyond the fade margin, which normally has a value of around 25 dBm.

The rain data used was from Okinawa, Japan. This site was chosen because Okinawa is in the region with subtropical climate and experiences rain all throughout the year because it is in the usual typhoon path. Of the one year data, 11% has rain events on which the proposed reconstruction method was done. The measured link attenuation is an integrated attenuation over the link path, thus the link will register attenuation even if only one part has rain. All kinds of rainfall from very light to violent rain were considered, and the rain cloud size varied from localized to widespread rains. There are 12,645 instances in time that the 25 sq. km. area has rain, regardless of rain cloud size, therefore a total of 316,125 data points were reconstructed.

The reconstruction can be evaluated either as a *false positive* or a *false negative.* The *false positive* rate gives the proportion of reconstructed locations that have nonzero computed rain rates when there is zero rain in the actual data. On the other hand, the *false negative* rate is the proportion of the reconstructed locations with no computed rain rates when in fact there should be. This can be considered as the No Rain threshold, which takes into account only the presence or absence of rain. The false positive rate for the case of 2 crossing links is 9.6% or 30,378 data points, while the false negative rate is 1.3e-4% or only 41 data points. The high false positive rate can be attributed to the spreading of the specific attenuation into neighboring areas during the reconstruction process. Figure 3 shows an illustration for this. The reconstructed area shows some small rain rate in areas where there is no rain in the original data (upper left-hand side). However, the high false positive rate is not a major problem because the reconstructed specific attenuations are very small such that the corresponding rain rate is also negligible. This small amount of attenuation is usually not noticed in real-time monitoring of the links. On the other hand, the very low false negative rate means that the proposed method was able to detect more than 99.999% of the rainfall areas.

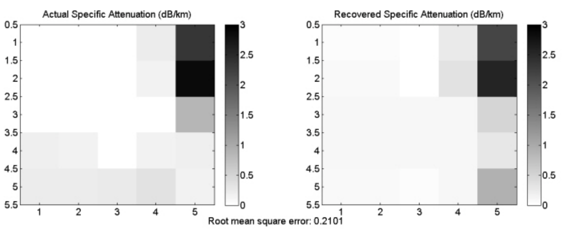


Fig.3: *Recovered specific attenuation that causes high false positive rate.*

The same process can be done for the case of the three links crossing a single area. From Fig. 2b it can be seen that there are a total of 19 links in the 25 sq. km. area. The link attenuation input to the compressed sensing algorithm is derived the same way as Eq. 4, and this will again be the input for the Matlab program, with the same lower and upper bounds as before. The simulation results verified that increasing the number of links in an area will increase the accuracy of detection. The false positive rate for the case of 3 crossing links is 4.03% while the false negative rate is 5.7e-5% or only 18 data points.

Aside from the rain location, the proposed method can also reconstruct the magnitude of the specific attenuation, which in turn indicates the rain rate in that area. To evaluate the magnitude reconstruction, the data were divided into 5 categories with respect to rain intensities: no rain, light, moderate, heavy, and violent rain [18]. Table 1 lists the categories and their corresponding specific attenuation. The number of data points in the original data set that satisfy each category are counted and compared to the reconstructed values. The root mean square errors for both the 2-link and 3-link reconstructions were also given.

The number of data points per rain rate category indicates the number of times that rain rate was seen in the 25 km square area for the whole data set. There are a total of 12, 645 instances with rain, bringing to a total of 316, 125 data points. As can be seen in Table 1, the data points decrease with increasing rain rate because the heavy and violent rains are less likely to happen than the light rains. Also, as mentioned before, even if only one part of the whole area has rain, all of the 25 points will be considered. This is the reason why there are a significant number of data points that have no rain. Since the specific attenuation due to rain was calculated straight from Eq. 1, the areas with no recorded rain are given a corresponding specific attenuation of 0 dB/km. This does not mean that the area does not suffer from any attenuation, only that it does not suffer any attenuation due to rain at that point in time.

Table 1: *Evaluation of Recovered Values Based on Rain Rate.*

Rain Rate (mm/hr)	Specific Attenuation (dB/km)	# of Data Points	RMS Error (2L)	RMS Error (3L)
No Rain	0	148,483	0.0561	0.0215
Light (<2.5)	< 0.40	105,761	0.1099	0.0596
Moderate (2.5∼ 10)	0.40 ∼ 1.46	49,801	0.2701	0.1636
Heavy (10∼ 50)	1.46 ∼ 6.65	11,536	0.7724	0.4598
Violent (>50)	> 6.65	544	2.3699	1.2728

From the results in Table 1 it can be seen that the proposed method can estimate the magnitude of the specific attenuation very well. The first two categories compose 80% of the data and they have very small errors. Moreover, these rain rates generally do not pose any risk. Moderate rain composes 15.75% of the data and its RMS error of 0.2701 for the 2-link case and 0.1636 for the 3-link case can still be considered negligible because the moderate rain rate in the actual data would still be reconstructed as moderate rain. Heavy rain, which can cause specific attenuations up to 6.65 dB/km, is only 3.6% of the whole data set. Reconstruction for this category has a 0.7724 error. The violent rain category, which comprises 0.17% of the data, has the biggest error of 2.3699. These errors are caused by the reconstruction process normalization of peak values to the neighboring areas. High specific attenuation values in the original data get distributed to other areas during recovery, causing a decrease in the recovered value. It is however important to note that the largest values from heavy rain and violent rain categories are most probably surrounded by other peak values, causing the overall link attenuation to be almost equal or more than the fade margin. When a microwave links received signal level goes beyond the receiver sensitivity, it will also have reached the maximum attenuation that it can record. In this regard, determining the location of the peak attenuation is more practical than verifying the accuracy of the recovery.

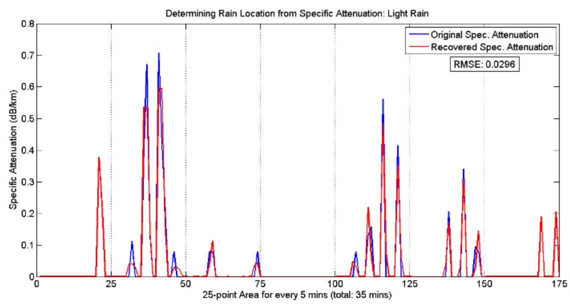
Fig. 4 shows some example of the rain area location detection in terms of specific attenuation. For the horizontal axis, the rainfall at the p-th area out of 25-point areas at the time 5q-minute corresponds to the index

$$i = p + 25q \tag{6}$$

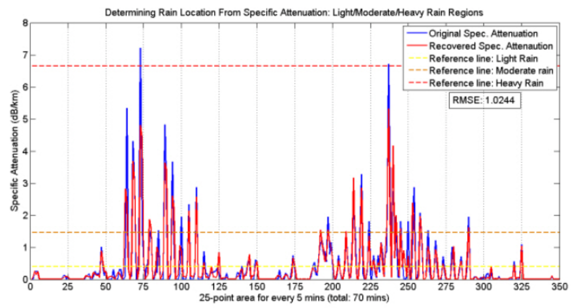
Fig. 4a and 4b shows detection on different rain regions. It is obvious from these two examples that the proposed method can effectively identify the location of rain. The error in example (a) is very small, and it was able to detect the light rain very well. In fact, the reconstruction was also able to show the length of the rain event. For the first five minutes (1-25, q=0), it can be seen that only one part of the 25-point area has rain. In the next 5 minutes (26-50, q=1), the rain has become more widespread and stronger. In another five minutes (51-75, q=2) the rain has significantly decreased, and was gone in another five minutes (76-100, q=3). The same pattern can be seen in the remaining 15 minutes (101-175, q=4-6).

Fig. 4b, on the other hand, shows location detection across three rain categories. Again, location detection was done very effectively. The reliability of the recovered magnitude is also best in light rain and gradually decreases as the rain gets more intense. Even so, the overall rms error for this 70-minute event is only 1.0244.

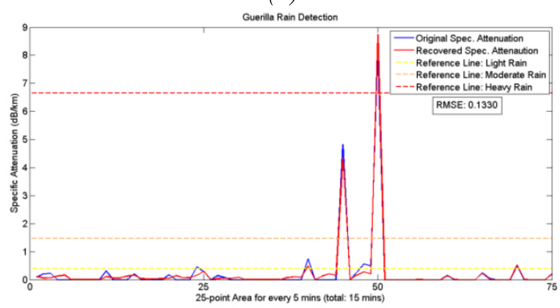
Another important rain event that the proposed method was able to detect is the presence of localized heavy rain. Fig. 4c shows an example of a very intense rain event that had an intensity of a violent rain. In this span of 15-minute data, the area was having very light rain, then the torrential rain, and then light rain again. This shows the swiftness of the event. The recovered specific attenuation magnitude is also very close to the actual value, with an error of only 0.1330.



(a)



(b)



(c)

Fig.4: *Rain location detection for (a) light rain, (b) light to heavy rain, and (c) guerrilla rain.*

Another set of figures are shown in Fig. 5, where the rainfall field reconstruction within the 25-point area is illustrated, showing the location and intensity of the specific attenuation at a given time. Different rain intensities were chosen to illustrate the performance of the reconstruction method. The reconstruction was not dependent on the rain rate, since even for very light rains it still performed well. The rms error is also given for each example. How the reconstruction process spreads out the values to neighboring areas is obvious when the simulation results are compared to the actual values, but the error is still negligible. In fact, the overall error for the 13-month data is only 0.2201.

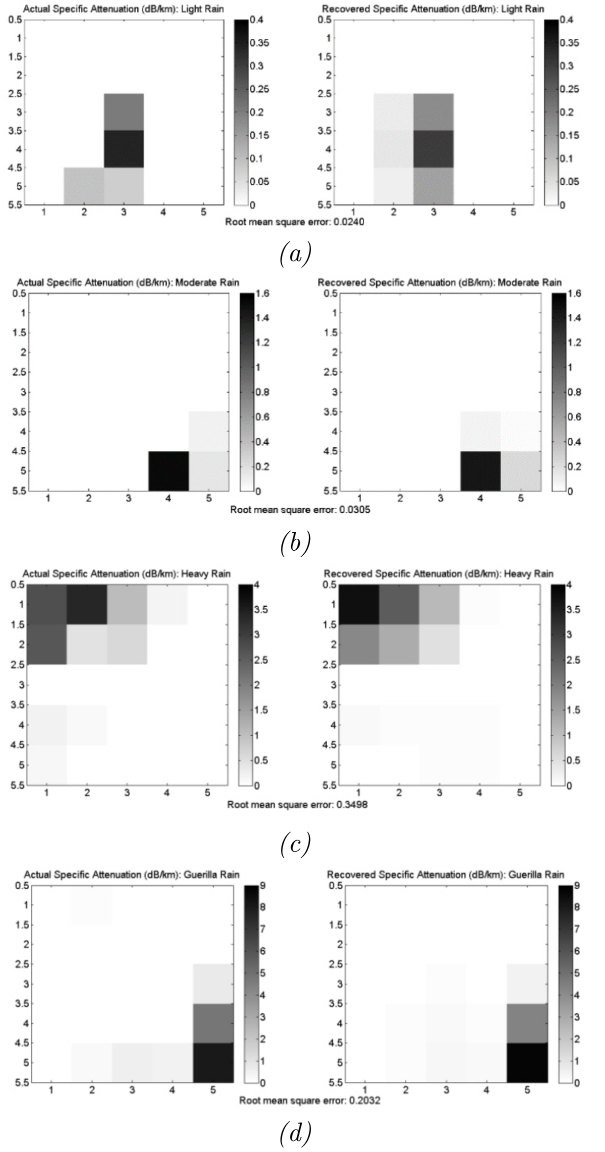


Fig.5: *Rainfall field reconstruction for (a) light rain, (b) moderate rain, (c) heavy rain, and (d) guerrilla rain.*

4.2 Reconstruction at Different Climates

The discussion so far involved data from the subtropical region of Okinawa, but it is also interesting to explore how the proposed method will perform in other climates and weather patterns. In this paper, two other locations were chosen - Tokyo and Hokkaido in the mid-latitude region. Tokyo is a highly-urbanized city with characteristic small-scale weather patterns, while Hokkaido has a climate similar to temperate countries. The three locations were chosen to show the effects of different possible rain types and durations.

Table 2 shows the percentage of rain events for the three locations. It can be seen that in terms of number, Hokkaido has the most number of rain events, followed by Tokyo, and then by Okinawa. In the same table, the false positive and false negative rates are also given, along with the corresponding rms error. It can be seen that Hokkaido has the worst FPR, meaning in the reconstruction, there were areas that have rain when there shouldnt be. However, in Table 3 it can be seen that more than 90% of the data for Hokkaido has very little or no rain at all and the important rain rates are actually less than 1% of the data. This means that most of the recovered rain rates for the Hokkaido data are small enough to be considered as negligible. Therefore, high FPR is acceptable when we know that the recovered rain rates are negligible. The same can be said for Tokyo and Okinawa, where the majority of the data are in the Light Rain and No Rain categories. The FNR in all three locations are very small, indicating a good detection rate for the proposed method. The rms error values in Table 2 were calculated using the reconstruction values and regardless of the rain rate category. Because of this, large rms errors in the heavy to violent rain categories affect the overall rms error. The FNR error for Tokyo shows this. The FNR for Tokyo is between that of Hokkaido and Okinawa but its FNR error is slightly higher than that of Okinawa. This does not necessarily mean that the detection done in Tokyo is less accurate, just that the absolute values of the data used produced an error that is more or less similar to that of Okinawa. The errors per category shown in Table 3 indicate that the error values for Tokyo are between Hokkaido and Okinawa.

From Table 2, it can be seen that the FPR is very much larger than that of the FNR. As mentioned before, this is because of the spreading of the rain rates to neighboring areas, usually at a lower rain rate. This means that there are many reconstructed data points that have rain values when there should be none. The original FPR is calculated using this No Rain threshold (NR-thresh), which means that the identification of areas with rain depends on whether there is value or not, regardless of the intensity of the rain. However, in reality, these false positives have very small values, in fact very close to 0, that they are practically negligible. This means that improvement in the FPR can be achieved if another threshold is implemented. Table 3 shows how the FPR and FNR are improved when the Light Rain threshold (LR-thresh) is implemented. This threshold means that all values that are considered light rain (rain rate of less than 2.5mm/hr and specific attenuation of less than 0.40 dB/km) are considered No Rain areas. With this threshold, the values of FPR and FNR are improved and almost equal to 0.

The evaluation of recovered values based on rain rate is shown in Table 4. Even though Hokkaido has the most number of rain events, it has the least number of destructive rain rates (Heavy and Violent Rain categories). In contrast, Okinawa has the least number of rain events but it has the most number of destructive rain rates. This is to be expected since Okinawa is in the subtropical region that experiences more typhoons throughout the year. In terms of error in recovering the values, it seems that the higher number of extreme rain events, the error is also higher. Tokyo is geographically between Hokkaido and Okinawa, and results for Tokyo are also between the results of the other two locations.

One interesting thing to note for Tokyo is that the percentage of light rain is relatively higher than those for the other two locations. Although it doesnt have as much destructive rain events as Okinawa, it does have a lot of light rain (more than 50% of the whole data). Although the percentage is large, this rain rate intensity does not pose any significant threat in terms of landslides and flash floods. The weather patterns in a highly urbanized city like Tokyo is important to study because meteorologists are now seeing patterns that are noticeable in urban cities but not in rural areas in the same latitude.

In all three locations, the percentage of rains in the heavy and violent rain rate categories is less than 5% of the data, and the error in recovery is also not that big. A more significant error is in the violent rain category (more than 1dBm). However, in practice the link may have possibly gone down already at these rain rates. This means that it would be hard to determine the exact amount of link attenuation, and what is known for sure is that the rain rate is very high already. In this case, the error in attenuation recovery is not so significant anymore, but what is now more important is classifying the rain as violent and that it can possibly trigger disasters like flash floods and landslides.

Table 2: *False Positive and False Negative Rates for Three Different Locations.*

Location	% of Rain Events	EPR (%)	FPR RMS Error	FNR (%)	FNR RMS Error
Hokkaido	13.4	10.3	0.05	7.34e-3	0.09
Tokyo	11.26	8.7	0.08	6.54e-3	0.14
Okinawa	11.09	9.6	0.12	1.2e-2	0.13

Table 3: *False Positive and False Negative Rates for Three Different Locations, with Threshold.*

Location	FPR (NR-thresh)	FPR (LR-thresh)	FNR (NR-thresh)	FNR (LR-thresh)
Hokkaido	10.3	2.46e-4	7.34e-3	3.11e-6
Tokyo	8.7	7.78e-5	6.54e-3	0
Okinawa	9.6	1.26e-3	1.2e-2	0

5. DISCUSSION AND CONCLUSION

This paper has proposed the use of compressed-sensing based specific attenuation reconstruction from measured link attenuations for the purpose of determining the rain location in a given area. Simulation results show that given a 10-link microwave mesh network in a 25 square kilometer area, the rain location and corresponding specific attenuation values can be effectively determined, with errors that are almost practically negligible. If the number of links crossing a single area is increased, the accuracy of detection and reconstruction for that area also increases. The proposed method proved effective for different rain intensities (light, moderate, heavy, and violent rains). More importantly, it was able to detect the presence of localized heavy rain, with the recovered value very close to the actual value. This can help in mitigating the effects of rain-related disasters like landslides and flash floods.

The proposed method was also applied to locations with different climates and weather patterns. The results show that the method can still reconstruct the rain fields well, and the errors are negligible for practical purposes. These errors are so small and usually not noticed in real time monitoring of microwave links.

The rain field reconstruction was done using a compressed sensing-based algorithm and without using any conventional weather sensing equipment. This shows the advantage of using the proposed method in areas with not much weather radars but with many microwave communication links deployed, like the tropical countries. The scale and temporal resolution of the microwave mesh networks also make it ideal for detecting localized heavy rains that are common in tropical countries. These torrential rains are the usual cause of river swelling that leads to flash floods, and by detecting the presence of these rains, a disaster might be avoided.

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Table 4: False Positive and False Negative Rates for Three Different Locations, with Threshold.

	Hokkaido % of Data Points Total: 381450	Hokkaido RMSE	Tokyo % of Data Points Total: 321025	Tokyo RMSE	Okinawa % of Data Points Total: 316125	Okinawa RMSE
No Rain	47.09	0.0377	28.94	0.0520	46.97	0.0561
Light Rain	44.56	0.0487	53.81	0.0564	33.46	0.1099
Medium Rain	7.96	0.1402	15.07	0.1755	15.75	0.2701
Heavy Rain	0.38	0.5143	2.03	0.6297	3.65	0.7724
Violent Rain	4.98e-3	1.3318	0.15	1.7837	0.17	2.3699

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