The Challenges of using Wireless Mesh Networks for Earthquake Early Warning Systems

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***Abstract*—The total cost of an Earthquake Early Warning System (EEWS) can be substantially decreased by using Wireless Mesh Networks (WMNs), which are inexpensive computer networks whose nodes communicate wirelessly using a license-free spectrum in a self-organized manner. The Early Warning System triggers on the small-amplitude, but fast P-wave in order to shutdown critical infrastructures before the destructive, but slow S-waves arrive only a few seconds later. It demands low-latency communications of high robustness. We conducted shakeboard-based measurements using IEEE 802.11a/b. Innovatively, our tests show that already for the slight shaking related to P-waves representative for strong ($M_w > 6$) and nearby (epicentral distance < 40 km) earthquakes, the performance of the wireless communications can be considerably affected at the very moment when the Early Warning system is supposed to be used. We observed swift link quality oscillations of up to 10 dB within only half a second. The more an environment is vulnerable to multi-path interference and shadow fading, e.g. no line of sight (NLOS), the more erratic are the wireless links between nodes. However, for clear line of sight (LOS) the influence of the vibrations is negligible. We recommend several measures that should be applied in order to make the unique use case of Earthquake Early Warning, nonetheless, well-functioning on top of a Wireless Mesh Network. A higher fade margin, in our setup at least an additional 5 dB, should be included to cope with sudden link fading. Moreover, antenna diversity should be enabled as it strongly mitigates the adverse effects of shaking.**

***Index Terms*—Wireless Mesh Networks, Earthquake Early Warning Systems, Measurements**

I. Introduction

Earthquakes belong to the most devastating natural hazards. They do not only cause damage to economic infrastructures, but also cause the loss of human life. Several megacities like San Francisco, Tokyo or Istanbul are at risk. Such cities do not only inhabit a large number of people, but they also constitute the economic heart of the region.

At present, several countries have an Earthquake Early Warning System (EEWS) in operation to protect its people and economies [1], [6], [10]. The current systems consist of only a few but expensive seismological stations, where all signals are sent to a central data management center before being processed. Each station alone can cost from 1,000's to 10,000's Euro. However, they are not only expensive at purchase time, but also costly in terms of maintenance. Therefore, EEWSs of sufficient quality are often beyond the financial capabilities of many high-risk countries.

The novel telecommunications technology of Wireless Mesh Networks (WMNs) might make EEWSs affordable and ubiquitous. WMNs are self-organized and automatically configured computer networks. Thus, hardly any human intervention is required. Their deployment is simple and inexpensive as they use commercial off-the-shelf hardware and operate in the license-free Industrial, Scientific and Medical (ISM) radio spectrum. In contrast to traditional seismological stations, wireless nodes cost only a small fraction – about 100 Euro at the time of writing.

In recent years, WMNs have been primarily used to build ad-hoc telecommunication infrastructures from scratch or as low-cost alternatives to traditional networks. Since June 2006, WMNs have been evaluated for their use as part of the "Seismic eArly warning For EuRope" (SAFER) project [12]. Another project called "Earthquake Disaster Information System for the Marmara Region, Turkey" (EDIM) started in April 2007 [5].

An Earthquake Early Warning System is feasible because earthquakes cause two basic kinds of seismic waves: P-waves (from Latin *prima unda*, i.e. primary waves) and S-waves (*secunda unda*, i.e. secondary waves). The harmless P-waves are almost twice as fast as the S-waves, which cause most of the destructive shaking [18]. Therefore, the time interval between the detection of the fast P-waves and the arrival of the slow S-waves, commonly termed 'warning time', depends on the distance of a target area, usually a city to be protected, from the hypocenter. Typical values of the warning time range between a few seconds, e.g. it might be as low as 4 seconds for Istanbul, to several tens of seconds for Mexico City. Although for the worst case scenario this short warning time is not enough for people to leave their houses, this can still be sufficient to mitigate secondary damages like fire outbreaks. For instance, critical systems like nuclear reactors or the gas and power supplies can be safely shut down.

The low-cost aspect significantly favors the use of WMN. Moreover, since commercial off-the-shelf hardware is inexpensive, this also allows for more sensor nodes and hence much denser sensor networks. These can provide more detailed, higher resolution information than traditional seismic networks with only a few powerful seismological stations spread on a large area. The use of low cost equipment also allows every household to become part of the network. Each household that purchases such equipment could also receive alarms and not only government agencies and companies.

In the aftermath of an earthquake the WMN might also provide a first telecommunication infrastructure for rescue activities, while at the same time being able to detect and issue warnings for aftershocks. Due to its self-organizing character and low power consumption, the network can easily cope with the outage of single stations and still be well functioning after an earthquake. A WMN is not only easy to deploy and setup, but its equipment is also easy to transport due to its low weight and small size. Thus, task forces like the German Task Force for Earthquakes, could take advantage of such a system to install a dense strong motion WMN immediately after a catastrophic earthquake.

II. Requirements of an EEWS

A. Operation

For Early Warning based on WMNs, the stations, or nodes, are deployed in the city itself. This approach is called an On-site system – in contrast to Front-detection systems, where the stations are placed near to the expected epicenter. The time lag between P-wave detection and the beginning of the strong shaking by S-waves might be only a few seconds. The lower the distance of a site to the hypocenter, the shorter the interval becomes. Due to the short notification time, the actions taken by a customer of an EEWS must be automated. Therefore, false positives are to be avoided by all means. Shutting down a nuclear power plant, or the gas and electricity supply of a whole city might itself cause severe problems.

Several algorithms exist for P-wave detection at a single station. One of the simplest yet commonly used single-station algorithms for detecting an event is the Short Term Averaging / Long Term Averaging (STA/LTA) trigger [16]. The acceleration values of the vertical component are averaged over a relatively long period of time, e.g. some seconds. This is the LTA value. It is set in relation to the STA value, which is calculated for a shorter period of time, e.g. only a fraction of a second. If the acceleration values remain constant, the STA/LTA ratio equals about 1, since both STA and LTA are about the same number. However, if the STA value suddenly rises due to shaking, while the LTA remains almost constant due to its longer time window, then the STA/LTA quotient exceeds a specific threshold value. If, for instance, a threshold level of 4 is considered suitable for the detection of an event, then every time that the STA is 4 times higher than the LTA an earthquake is detected.

Of course, STA/LTA just like any other single-station algorithm might also misleadingly trigger due to man-made or other seismic noise. For instance, STA/LTA might cope with natural seismic noise, which fluctuates slowly. However, it is less effective for seismic noise of a bursting nature like vibrations from a nearby construction site or strong winds. This might occur more often for Earthquake Early Warning based on WMNs. Normally, seismometers are fixed in the basement or a borehole in order to minimize seismic noise and only measure the real ground motion. However, for WMNs a seismometer is combined with a wireless router. For wireless networks, it is recommended to mount these nodes on top of a house or at least near a window because wireless propagation, e.g. IEEE 802.11, is much better with clear line of sight between participating routers. Hence, a tradeoff between accuracy for seismologic measurement and good propagation conditions for wireless communications exists.

To trap false positives when using WMNs, the seismic stations, or wireless nodes, need to interact and repetitively communicate its status with each other. These status messages are of small size, but the more often they are exchanged, the sooner an alarm can be confirmed or dismissed. The EEWS might only issue an alarm to its customers, if a certain number of stations have triggered [6]. Thus, a local vibration can be efficiently ruled out.

It is worth to note that there is no strict requirement for communication during the powerful S-wave, when the shaking is strongest. However, it is more needed at P-wave time for Early Warning. Here, the wireless communications must be optimized for low latency and high robustness of its status messages.

B. P-wave Displacement

a) Challenges when using WMNs: Building EEWSs using WMNs based on IEEE 802.11 is a new research topic. Thus, hardly any related work is available. Most of the time the WMN is quasi-static, so only little mobility due to moving obstacles, e.g. walking people, exists between the nodes. Otherwise all nodes fixed to a seismometer would consider every kind of movement as the outset of a tremor. However, since seismometers record movements and take the strength of shaking as a measure of an earthquake's magnitude, this also means that at the very moment that the WMN is supposed to be used for Early Warning its nodes might start moving or at least the surrounding obstacles like buildings or trees. This kind of movement can be translated to mobility as known from the networking world. Taking this kind of motion into consideration is important, because it might result in multi-path or even shadow fading corrupting the wireless transmission [17, Sec. 2.1]. Assume that the quality of the wireless links has been measured over the past time using a popular metric like Expected Transmission Count (ETX) [4]. Some links were found of good, some of bad quality. Imagine an earthquake occurred now with the STA/LTA algorithm triggering on a P-wave. Would the displacement of nodes and the resulting mobility due to P-wave shaking have an impact on the quality of the wireless links or is the quality the same as estimated beforehand? Hence, is it possible that a link considered of good quality suddenly becomes bad as the P-wave arrives?

For the means of an EEWS, the amplitude and frequency of shaking caused by P-waves must be estimated. Knowing these parameters its influence on the WMN can be evaluated. The impact of a tremor depends on various factors like its magnitude (which is logarithmical), focal depth, the kind of rupture as well as the epicentral distance and geology of a site. Hence, exact numbers are hard to calculate. Instead, a possible range of amplitudes and frequencies should be stated by considering empirical values from past earthquakes with different characteristics.

b) Related Work: Wu and Zhao refer to the peak amplitude of displacement within the first three seconds after the arrival of the P-wave as P_d [21]. They use this P_d value to estimate the magnitude of earthquakes. They selected 25 regional earthquakes from the Southern California Seismic Network catalog with moment magnitudes (M_w) greater than 4.0, among which is also the Northridge 1994 earthquake with 6.7 M_w and the Hector Mine 1999 tremor with 7.1 M_w. Even for the strong magnitudes of Hector Mine and Northridge the displacement due to the incoming P-waves is very little. The highest recorded P_d is at the hypocentral distance of 30 km for the Northridge tremor with 0.4 cm. For most ground motion records, the displacement is even below 0.1 cm. However, they suggest that theoretically P_d could be several centimeters for short hypocentral distances like 15 km.

Wurman et al. present complementary results for northern California, also including Hector Mine and Northridge [22]. They show peak displacement values scaled to an epicentral distance of only 10 km. For such a very short distance, the highest P_d value of all earthquakes is at 2 cm, but much less for most other tremors.

In an earlier work, Wu et al. came to similar results [20]. For 46 Taiwanese earthquakes, including the Chi-Chi 1999 tremor with 7.6 M_w, the P_d value is below 0.1 cm for all records. However, it must be stated that the epicentral distance is above 80 km for the Chi-Chi record.

In 2007, Wu et al. published a further study summarizing their Taiwanese and southern Californian results [19]. This time, they only show records for stations with an epicentral distance of less than 30 km. For all 199 stations from southern California the P_d value, that is, the peak displacement within the first three seconds, remains below 0.25 cm. From the 507 Taiwanese records only five stations yield a displacement above 2 cm, with one station, however, reaching an outstanding P-wave displacement of 6 cm.

The latest work is by Wu and Kanamori, where another 74 Japanese records are included [18]. For these, the P_d of four stations is above 2 cm with two of them at 6 and 7 cm, respectively. These examples exhibit extremely large P-wave shaking, against which the performance of an WMN should be measured since EEWSs are naturally designed to cope with the most severe earthquakes.

For Europe, including Turkey, to the best of our knowledge, there exists no publication yet on the amount of displacement caused by P-waves. However, it can be calculated from existing records, which are available on the CD-ROM “Dissemination of European Strong-Motion Data” [2]. It contains the acceleration time histories of all earthquakes in Europe and adjacent regions between 1971 and 1999. The Izmit 1999 tremor with a moment magnitude of 7.8 is also included. Its data are an obvious object of investigation, because it was a very strong earthquake on the North Anatolian Fault Zone very near to the megacity of Istanbul, which also the EDIM project focuses on. Moreover, Istanbul is also one of the test cities for the low-cost wireless mesh sensor nodes developed by SAFER [13].

The data from the seismological station of Iznik-Karayollari Sefligi Muracaati are of most interest since its distance of 39 km from the epicenter of the Izmit tremor is very similar to the one that would be expected for Istanbul. Fig. 1 shows the recorded data for this station. At top, the recorded acceleration values are given on which also the P-wave trigger, marked by

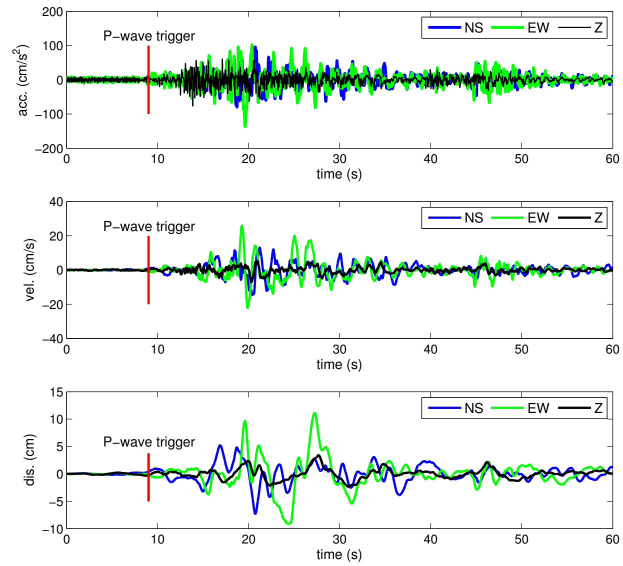

Figure 1. Ground motion for the Izmit 1999 earthquake (7.8 M_w) at the seismological station Iznik-Karayollari Sefligi Muracaati with an epicentral distance of 39 km.

the red line, is calculated using the STA/LTA algorithm. The acceleration values were recorded for all three orthogonal components: *NS* refers to the North-South direction and *EW* to the East-West direction on the horizontal plane. *Z* stands for the vertical movement. The middle plot shows the velocity values in cm/s, which were obtained by integration over the original acceleration values. At bottom, the displacement is given in centimeters. It was calculated by another integration [8]. The earthquake starts at about the ninth second of the record, which is also correctly marked by the P-wave trigger. About 6 seconds after the first initial P-wave the powerful S-waves arrive. This can be noticed by a much stronger amplitude from the 15$^{\text{th}}$ second onwards. The shaking only becomes weaker again after the 35$^{\text{th}}$ second.

From the perspective of wireless communications, only the first seconds following the P-wave trigger are of interest. This is the time window within the Early Warning would happen. Fig. 2 highlights the amount of displacement caused by P-waves at the station for this time interval. The peak amplitude of displacement equals about 1 cm for all components. Only at 15 seconds on the x-axis the displacement exceeds the 2 cm mark as the S-waves seem to arrive, and the shaking grows subsequently.

From Fig. 2, it is also obvious that the frequency of movement is quite low. Consider the blue line (*NS*), which also yields the maximum P-wave displacement of all three components. From the peak amplitude of 1.1 cm at the 10$^{\text{th}}$ second to the trough at 11.5 seconds with -1.5 cm only 1.5 seconds elapse. That is, the displacement amounts to only 2.6 cm in 1.5 seconds for *NS*. Adding the lower displacement values of *EW* (about 1 cm) and *Z* (hardly any) as directional vectors, the peak amplitude still remains low with at most 2 cm. The period is quite high with about 3 s ($0.\overline{3}$ Hz), if one considers the P-wave trigger mark as the beginning of a cycle.

These numbers are underlined by the acceleration values

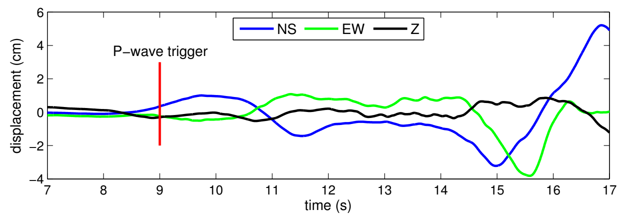

Figure 2. Detailed view of P-wave displacement for Izmit 1999 tremor (7.8 M_w) at 39 km epicentral distance (compare with full view at Fig. 1).

recorded at other seismological stations for the Izmit 1999 tremor, which are due to space limitations not shown here. The nearest station to the epicenter, Izmit-Meteoroloji Istasyonu, only 10 km from the strike slip, yields an amplitude of about 4 cm at P-wave time.

Altogether, for the strong Izmit earthquake amplitudes of up to 4 cm were measured at nearby seismological stations for the P-wave. The shaking frequency equals about 1 to $0.\overline{3}$ Hz (period of 1 to 3 s). However, as shown by Wu and Kanamori an amplitude of 6 or even 7 cm is also possible depending on hypocentral distance and magnitude of a tremor [18].

III. Impact of P-Wave Shaking on Wireless Communications

A. Theory

Wireless networks are different from their wired counterparts as they use a broadcasting medium where messages are not only interceptable by anybody but also a ubiquitous source of interference. The range of wireless communication is not fixed but depends on a variety of aspects. Generally, the higher the frequency of electromagnetic waves for a certain transmit power, the shorter the reception range. A useful wireless signal can get distorted by noise (thermal), interference or by the wireless channel itself [11]. In a mobile scenario distortions like Doppler effect, multipath and shadow fading may appear resulting in corrupted transmissions. Shadowing occurs when an obstacle, which attenuates electromagnetic waves, gets in between the transmitter and receiver. This can happen because the obstacle, transmitter and/or receiver are moving. Multipath fading occurs in a mobile environment where signals arrive via different paths at the receiver. Here a relative movement between sender and receiver in the order of a wavelength can cause constructive or destructive superposition of the signal at the receiver (Fig. 3).

The IEEE 802.11 standards use the 2.4 and 5 GHz bands of the public, license-free ISM spectrum governed by regulation authorities like the FCC in the USA or the ETSI in Europe. There is also a small ISM band at about 900 MHz: 902–928 MHz in the FCC domain, but only 868–870 MHz are publicly available in Europe, which is too narrow for a broadband signal like 802.11. However, the 900 MHz band would be highly attractive to Early Warning Systems as it offers a much wider communication range than 2.4 or 5 GHz due to its lower frequency. Moreover, being not standardized by the IEEE, it is less prone to external interference. With special permission by governmental authorities, which are often involved in EEWS projects anyway, this band might nevertheless be used.

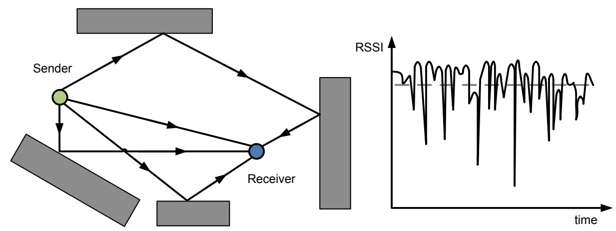

Figure 3. Signal strength of the received signal (RSSI) in case of a relative movement between sender and receiver in a multi-path environment. Adapted from [17].

IEEE 802.11b/g consists of 13 channels in the 2.4 GHz band for the ETSI and 11 channels for the FCC domain. It offers variable bitrates between 1 and 54 Mbps. The lower the bitrate, the more robust and less vulnerable it is to data loss because of a higher redundancy in the modulation [7].

The impact of multi-path fading depends not only on the relative speed but also on the wavelength which is calculated by:

$$\lambda = \frac{c}{f}\ , \tag{1}$$

where c is the speed of light, f the frequency in Hz and λ the resulting wavelength. The wavelength of 802.11b/g can be calculated as follows:

$$\lambda \approx \frac{300,000,000 \text{ m/s}}{2.43 \text{ GHz}} \approx 12.3 \text{ cm}$$

IEEE 802.11a operates in the 5 GHz band and provides eight channels for indoor and eleven (ETSI) or four (FCC), respectively, for outdoor use. Besides using a different frequency range, 802.11a works similar to 802.11g, because it uses the same modulation techniques and therefore offers the same bitrates. The wavelength for 802.11a can also be calculated using Equation 1 and equals about 5.8 cm.

The shorter the wavelength, the more vulnerable wireless communications are towards shaking, since only a small relative movement is sufficient to change superpositioning of different waves. So the RF band of 802.11a with a wavelength of only 5.8 cm is at higher risk than 802.11b's frequency band with a wavelength of about 12.3 cm.

B. Measurements

a) Setup: Sec. II provided a rough, but sufficient estimation of the amount of shaking that would be caused by a strong ($M_w > 6$) and nearby (epicentral distance < 40 km) earthquake at P-wave time. A test environment was created to emulate the expected shaking as good as possible. The purpose was to examine its impact on the performance of wireless communication. The test methodology will be explained briefly with the most important parameters listed in Table I.

One node was mounted on top of a four-story building at the Humboldt University of Berlin. This node served as a sender issuing 50 packets per second with a size of 100 bytes each. The rather small size was chosen, because the data that needs to be transported by Early Warning messages is also rather small [6]. The node had two radio transceivers, one tuned to channel 14 (2.484 GHz) for 802.11b and the other

Parameter	Value
RF channels	2.484 GHz (ch. 14, DSSS) with 1 Mbps
	4.92 GHz (ch. 184, OFDM) with 6 Mbps
Transmission powers	2–16 dBm in steps of 2 dBm
RTS/CTS	Disabled
Packet transmission rate	50 packets per second
Packet size	100 bytes
Transmission mode	Broadcast
Flow duration	20 sec
Shaking frequencies	$0.\overline{6}$ Hz (1.5 s period), 1 Hz (1 s period)
Shaking amplitudes	2 cm, 4 cm, 6 cm (only for $0.\overline{6}$ Hz)
Still points	−6, −4, −2, 0, 2, 4, 6 cm
Receiver locations	Indoor
	distance to sender: 32 m
	line of sight: reduced
	reflecting obstacles: many
	Outdoor
	distance to sender: 82 m
	line of sight: excellent
	reflecting obstacles: few

Table I
PARAMETERS FOR SHAKEBOARD MEASUREMENTS.

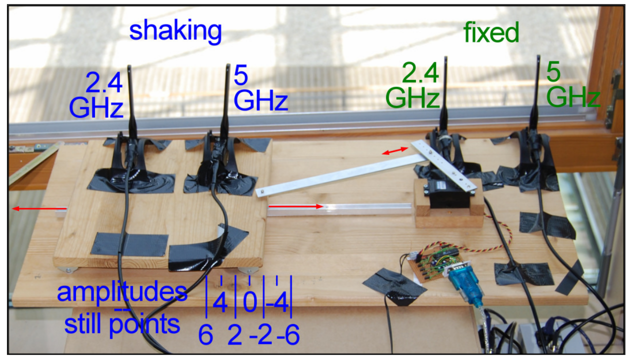

Figure 4. Shakeboard at indoor window location: Antennas of left receiver are put on the shaking table moving along the given amplitudes (cm). The right node receives at the same time, but is fixed.

used channel 184 (4.92 GHz) for 802.11a. These channels are outside of the bands provided by the ETSI and FCC. However, they are available for public use in Japan, which is also exposed to high earthquake risks. The channels were chosen in order to guarantee interference-free communications since all other channels provided by the ETSI are heavily used by our campus network.

The data packets sent by the roof-mounted transmitter were received by two other nodes (Fig. 4). Using pigtails the antennas of one node were placed on a shaking table (left node of Fig. 4), while another node was fixed next to it representing a non-moving receiver (right node). Each antenna was connected to a distinct Atheros radio card with antenna diversity disabled. The wireless driver was MadWifi version 0.9.4. The Linux kernel 2.6.22 was used as operating system, the Click Modular Router software version 1.6 for packet generation and capturing. MadWifi's spurious ambient noise immunition was disabled to ensure a sound test environment [15].

The shaking table was configured to move along a horizontal line. Different amplitudes of 2, 4 and 6 cm were used (Table I and Fig. 4 bottom). Following the observations made in the last section, the shaking frequencies were chosen to be $0.\overline{6}$ and 1 Hz. To give an example, the setup with 6 cm amplitude and frequency of $0.\overline{6}$ Hz made the shakeboard move from −6 cm to 6 cm and then back to −6 cm within 1.5 seconds (one cycle). The data flow lasted 20 seconds. Hence, for the frequency of $0.\overline{6}$ Hz within one run $13.\overline{3}$ cycles were completed by the shakeboard.

Besides the shaking setups, measurements of equal duration (20 s) were also conducted at still (non-shaking) points of the shaking table. The table and with it the receiver were fixed at seven different marks (−6 cm to 6 cm in steps of 2 cm, Fig. 4 bottom). The purpose was to examine whether a relation between the link quality at these points and the swift movement along them during shaking exists. The still points were always measured immediately after running the shaking setups to minimize effects due to changes within the environment.

Two locations with different characteristics were used for reception. The first one was indoors at an open window of a neighboring house as seen in Fig. 4. From here, the sender (32 meters away) was hardly visible, since several rooftop steel girders spanned along the line of sight (NLOS). Multi-path and shadowing effects are supposed to be numerous here. The second location was outdoors about 82 meters from the rooftop sender. Here, the receivers had very clear line of sight to the sender (LOS). Multi-path fading should only play a minor and shadowing no role at all.

Since only two locations and hence distances between transmitter and receivers were chosen, the measurements for each amplitude/frequency combination were repeated with the sender using a lower transmission power. Altogether, eight different powers were chosen (2–16 dBm in steps of 2 dBm), of which the lower values of 2, 4 or 6 dBm were supposed to emulate longer link distances.

b) Results: Albeit the different transmission powers, the packet error rate was near zero for all test cases and transmission powers. The used modulations of DSSS and OFDM are redundant enough at low bitrates (1 and 6 Mbps), so that a small Signal-to-Noise Ratio (SNR) is sufficient for successful packet transmission. Obviously, this was the case here. However, since almost all packets were delivered successfully, this allows us to analyze their SNR values reliably. 50 packets per second were sent for 20 seconds, making a total of 1000 packets per measurement to form the basis for analyzing the impact of P-wave shaking.

The indoor window location is considered first. Fig. 5 plots the SNR values for the first ten seconds of the 6 cm / $0.\overline{6}$ Hz setup. The shaking (blue) and the fixed node (green) are shown with the SNRs they received for the same data packets. The fixed node remains very near to 32 dB. However, the shaking node's SNR values oscillate strongly from 33 to 23 dB, a difference of no less than 10 dB between maximum and minimum. If one looks carefully, one can recognize a repeating pattern lasting 1.5 seconds each. This equals the period of the shaking ($1/0.\overline{6}\,\mathrm{Hz} = 1.5\,\mathrm{s}$) and seems to correspond to one full cycle of the shaking movement.

Fig. 6 summarizes the variations of the packets' SNR for all setups using the bitrate of 1 Mbps at 2.484 GHz with a transmission power of 16 dBm at the sender. The

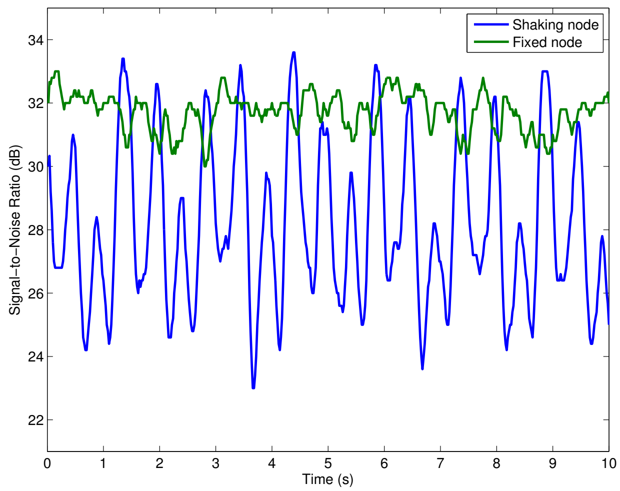

Figure 5. Signal-to-Noise Ratio of the first 10 seconds (500 packets) for shaking and fixed node (indoor location, 2.484 GHz, 16 dBm, shaking amplitude of 6 cm, frequency of $0.\overline{6}$ Hz). An averaging time window of 0.06 s (3 samples) was applied for smoother display.

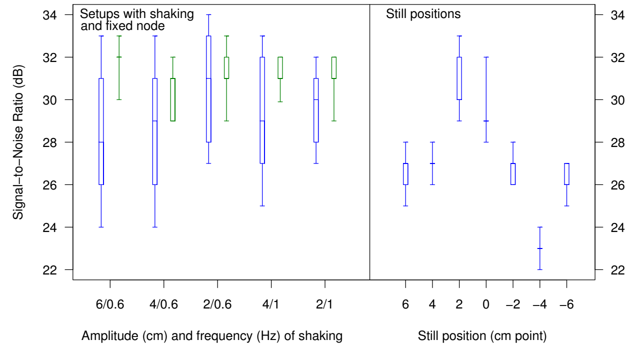

Figure 6. Distribution of Signal-to-Noise Ratios at indoor location for 2.484 GHz with 16 dBm. The left part shows boxplots for the shaking (blue) and fixed node (green), while the shakeboard was moving with the given amplitude and frequency. The right part depicts boxplots for the left, previously shaking node, now being fixed at still points. The lower and upper quartile are outlined as square bodies, including 50 % of all SNR values. The middle line of each body shows the median. The thin "whisker" lines mark the percentiles of 5 and 95 %, including 90 % of all samples.

shaking setups are depicted in the left part. The left, shaking node (blue) and the right, fixed node (green) received the same packets simultaneously. Quite obviously, the range of SNR values is much larger for the shaking node for all five amplitude/frequency combinations. For instance, in the setup with an amplitude of 6 cm and $0.\overline{6}$ Hz frequency, 50 % of all packets have a SNR between 26 and 31 dB, with the median at 28 dB. While this is a range of 5 dB for half of the packets, at the fixed node the lower (Q_1) and upper quartile (Q_3) coincide with the median (Q_2) at 32 dB. That is, at the fixed node at least half of the packets arrive with an equal SNR of 32 dB. The "whisker" lines, including the SNR of 90 % of all packets, have a similar difference in range: 24 to 33 dB for the shaking, but only 30 to 33 dB at the fixed node next to it. The SNR values at the other shaking setups are similarly distributed. The interquartile ranges ($Q_3 - Q_1$), including 50 % of all packets, are 3 dB (2 cm / 1 Hz) and 5 dB (all other setups). For the fixed node, the range is only 2 dB (4 cm / $0.\overline{6}$ Hz) and 1 dB for the last three setups. For the 90 % range, the differences are even bigger.

The results for the still points depicted in the right part of Fig. 6 are also quite interesting when compared to the shaking node in the left part. The SNR distribution is much narrower when the previously shaking node gets fixed at a still point. However, the ranges among the points themselves are quite heterogeneous. For example, the 2 cm mark has a median of 30 dB with Q_1 and Q_3 ranging from 30 to 32 dB. For the -4 cm mark, however, $Q_{1,2,3}$ coincide at 23 dB.

For all other power levels, the distribution of SNR for shaking nodes is similarly higher than for not shaking nodes at the indoor location and 2.4 GHz.

Contrary to the previous results, we hardly recognized a difference in the distribution for 5 GHz between the shaking and non-shaking cases at the indoor location and 16 dBm. The only noteworthy fact is that the interquartile range is generally higher with about 5 dB for all measurement cases compared to 2.4 GHz in Fig. 6. This might be caused by the shorter wavelength at the 5 GHz band, which is more vulnerable to multi-path effects in general. The SNR values of incoming packets with about 10 dB are also much smaller than for 2.4 GHz (circa 30 dB, compare with Fig. 6), since the attenuation is stronger for the higher RF band. This emphasizes the much shorter communication range of IEEE 802.11a compared to 802.11b/g. The uniformity of distribution for the 5 GHz band at the indoor location, however, might be caused by the fact that the interquartile ranges for the still points very much overlap themselves here. For the case of 2 dBm, the distribution of the still points is more heterogeneous. The difference of SNR ranges is again also greater between the shaking and fixed node for the shaking setups.

The above findings suggest that the amount of variance depends on whether the link qualities at the still points are heterogeneous or not. That is, the link quality oscillations during P-wave shaking are mainly inherited from the properties of the still points that the node passes along. It is even possible to reconstruct the shakeboard's movement from the oscillation of the SNR values. Due to space limitations this is not covered here.

After finding a strong impact of shaking on the wireless communication for the indoor location, we will now pay attention to the outdoor setups. Due to fewer obstacles shadowing and multi-path effects should not be that dominant here and other results might be expected.

Fig. 7 shows the variations of SNRs for the outdoor location, 82 m away from the sender. The bitrate is 1 Mbps (DSSS) at 2.484 GHz with 16 dBm. Interestingly, the difference in the variation range between shaking and non-shaking nodes is not very pronounced, although the still points show a big diversity among themselves as for the indoor location of Fig. 6. In contrast, the interquartile ranges including 50 % of all packets are even larger for the fixed node (green) than for the shaking node (blue) except for the case of 4 cm / 1 Hz. For the two shaking setups with 2 cm amplitude the spread is very little

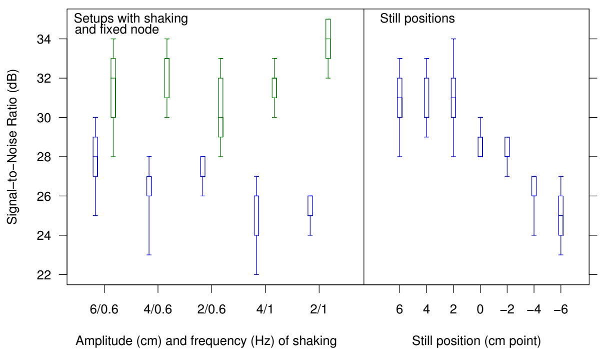

Figure 7. Distribution of Signal-to-Noise Ratios for outdoor location at 2.484 GHz with 16 dBm. Interpretation as explained at Fig. 6.

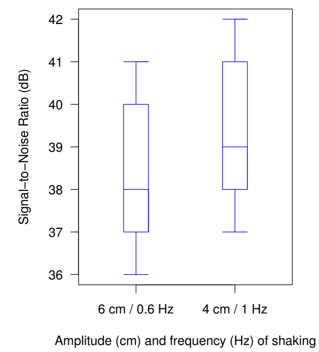

Figure 8. Repeated measurement for two shaking combinations. Setup as in Fig. 6, but with antenna diversity enabled (2.4 GHz, 1 Mbps, 16 dBm). The spread of SNR values is now decreased.

for the given surrounding with low multi-path interference. A difference between the shaking node and the measurements at the still positions when it gets fixed cannot be observed. Surprisingly, the fixed node's median is always considerably higher than for the shaking node. This might be caused by the fixed node being placed at a position of extraordinary quality and should not be overstated, as the still points of the previously shaking node show that high (6, 4 and 2 cm marks) as well as low SNRs are possible for this location.

For a reduced transmission power of 2 dBm the distribution is not as contrarian as for 16 dBm. However, for all five amplitude/frequency combinations the spread is not considerably higher for the shaking than for the fixed node. Generally, the SNR values of the shaking node do not have a substantially higher range of variation than the non-shaking nodes at 2.484 GHz, regardless of the transmission power.

The 5 GHz band shows a similar picture at the outdoor location. A difference in distribution between shaking and non-shaking cannot be observed for all setups at 16 dBm. For 2 dBm the distribution is equally uniform, except that the variance is less because of generally smaller SNR values at this low power level.

Generally, the impact of P-wave shaking seems evident for the indoor location with reduced line of sight. If shadowing and multi-path fading cannot play a significant role, as is the case for the outdoor location with a clear LOS, the impact is marginal.

Since the problems mainly seem to arise from shadowing and multi-path fading, we looked at possible solutions in order to alleviate the rather strong impact at such places. An obvious countermeasure would be to use antenna diversity to mitigate the influence of multi-path effects [9]. Most radio cards, including the used ones by Atheros, have two antenna connectors (*main* and *aux*). A second antenna can be connected to the *aux* socket and placed a few centimeters from the first one connected to *main*. For most off-the-shelf WiFi routers the default antenna separation is about 15 cm. Since this is more than the wavelength of 2.4 GHz (12.3 cm) and 5 GHz (5.8 cm) the two antennas will have different reception conditions, again due to multi-path effects. One differentiates between receive and transmitter antenna diversity. For receive diversity, the radio card listens to the SNR of both antennas during the preamble. The better antenna is used for packet reception. Transmitter diversity works by keeping statistics on which of both antennas received packets from a neighboring node more often. The antenna that more often had a better signal strength at reception is supposed to be superior for this node. If the receiving router now itself wants to transmit a packet to this neighbor, it uses the superior antenna. For the use case of an EEWS the benefits of antenna diversity are obvious. During shaking the antennas are at two distinct "still" positions. Therefore, it is statistically less likely that the positions of both would be of bad quality than if only one antenna, and position, was available.

Fig. 8 shows boxplots for two shaking setups with receive antenna diversity enabled. This was done by connecting the right antenna of the shaking node, previously at 5 GHz, to the *aux* connector of the 2.4 GHz radio card (Fig. 4). The separation between both antennas was 15 cm. Compare these boxplots to those of Fig. 6, where only one antenna was used. For 6 cm / $0.\overline{6}$ Hz the interquartile range is only 3 dB compared to 5 dB. 90 % of all values are between 36–41 dB, a range of only 5 dB compared to 9 dB.

The setup with the amplitude of 4 cm and 1 Hz frequency is similar, with at least 50 % of all packets having a SNR between 38 and 41 dB, compared to 27–32 dB. So the interquartile range is 2 dB smaller. 90 % of all packets are between 37 and 42 dB (5 dB range), compared to 25–33 dB with only one antenna (8 dB range). Noteworthy, the SNR values are generally about 10 dB higher for the setup with antenna diversity enabled. This might be largely caused by the fact that the radio card was always able to choose the better of two SNRs.

IV. Conclusions and Future Work

The use case of Earthquake Early Warning is unique and requires a special approach. Even though P-waves are non-destructive, they can cause slight shaking of a few centimeters for strong ($M_w > 6$) and nearby (epicentral distance < 40 km) earthquakes at the very moment, when the Early Warning System would be activated. From past earthquakes the amplitude of P-wave shaking could be estimated. Depending on the magnitude and hypocentral distance, it can range from

2 to 6 cm for worst-case scenarios. Of course, these are the scenarios where a fast and reliable EEWS is most needed. It was found that the sudden small-amplitude P-wave shaking can have an immense impact on the performance of wireless communications. The exact extent by which shaking affects the quality of a wireless link depends on the surroundings of the transmitter and receiver. If there is an almost clear LOS with only few obstacles between both transceivers, then the influence is small. However, the more an environment is affected by shadowing and multi-path fading effects, the stronger does the link quality oscillate along with the nodes' motion. For an EEWS, one should require a much higher fade margin than usual. In our case, an additional 5 dB needed to be included. That is, the nodes should be placed closer than done for other use cases. It should also be mandatory to equip every radio card with two antennas and to enable antenna diversity in order to alleviate fading. If possible, the nodes should also be positioned in such a way that the displacement of a few centimeters has only a minimal influence on the line of sight between the transceivers. By doing so, the impact of P-wave shaking can be strongly mitigated.

However, within a self-organized WMN the deployment of nodes can only be planned to some extent. Usually, each node has at least some neighbors at the transmission borderline. The swift link quality fluctuations due to multi-path effects and shadowing are very difficult to handle with today's pro- or reactive unicast routing approaches which infer the current quality of links from past measurements. These estimations are not only used for routing, but they also form the basis for clustering and cluster head selection as done by other Early Warning projects like EDIM or SAFER [14]. If an earthquake occurs, a link considered of good quality might suddenly become bad as the P-wave arrives, rendering a previously selected routing path unusable. A totally different communications approach like opportunistic routing might be worth considering for the future. Here, radio links of erratic qualities, which would normally be avoided by current routing protocols, can be used on a trial and error basis [3]. While the concept of opportunistic routing might be beneficial for WMNs in general due to its broadcast medium with lossy links, it should so even more for the application of an EEWS, where link qualities are extremely fluctuating. In the same way that antenna diversity is able to mitigate the swift link quality oscillations on the small scale, opportunistic routing as a form of macrodiversity should be able to compensate these fluctuations by employing different neighbor nodes with distinct receive conditions. In the future, such an approach is worth considering, as it might be better suited for the use case of Earthquake Early Warning. Moreover, it seems to be advisable for projects to apply for a permission to use the non-standard 900 MHz band which would allow a wider coverage with less external interference. Only ground motion has been considered in this paper as measure of P-wave shaking, because these are the numbers recorded at seismological stations. Examining the rooftop shaking of buildings, which is expected to be much stronger, would have been more appropriate for WMN and will be further examined in our future work.

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