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Wireless Sensor Networks: Towards Resilience Against Weather-Based Disruptions

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Abstract **– The article discusses vulnerability of wireless sensors networks to weather-based disruptions considering the opinions of different experts published in a range of scientific materials. The introduction provides a brief overview of wireless signals in real world conditions focusing on how weather affects signals (rain, fog and clouds, snow, hail, lightning, wind, bodies of water, trees and physical obstruction). Information about the effects of weather on wireless sensor networks using Free Space Optical / Radio Frequency (FSO/RF) communication is then provided. Finally, the impact of weather conditions on MANET routing protocols is considered theoretically, and experimental simulations are performed by comparing the sustainability of different protocols to different weather conditions. After analysis of experiment results, ideas on how to decrease vulnerability of wireless networks to weather-based disruptions are discussed.**

Keywords **– Computer simulation; Industrial communication; Wireless LAN; Wireless sensor networks.**

I. Introduction
How Weather Affects Wireless Signal

Recent research has demonstrated that different weather phenomena affect the wireless links in a variety of ways. One of the strongest correlations that we have seen is that of precipitation and network performance degradation [1].

Previous studies have shown that absorption, scattering, and refraction of micro electromagnetic waves by atmospheric gases and precipitation is an important limiting factor in transmission distances in wireless communications. In fact, rain, fog, and clouds become a significant source of attenuation when wireless networks operate using the microwave spectrum [2]. The most important factors are examined further.

A. Rain

The larger the drops, and the more of them there are, the more wireless signal will be scattered. Very often strong rain can weaken wireless signal more than any other weather. Absorption due to precipitation is one of the most serious problems with the propagation of millimetre range waves. The presence of raindrops can lead to a significant decrease in the reliability and performance of the communication channel, and during periods of heavy rain it can be a decisive factor. It is quite difficult to consider the effect of rain on the propagation of millimetre range waves [3], since it is necessary to determine the shape and size of a droplet, the frequency of droplets falling, the intensity of precipitation, etc. The most common formula for estimating the absorption due to the rain is: $A = aR^b$, where absorption is measured in decibels per kilometre (dB/km), rain intensity is measured in millimetres per hour (m/h), and parameters a and b depend on the size distribution of the droplets and on frequency. Moreover, the absorption also depends on the polarization of the electromagnetic wave. For certain values of a and b, the absorption depends on the intensity of rain, R. The main concern is about the periods of time during which the intensity of rain exceeds a certain threshold. It all depends on the climate zone. There are tables developed by the International Telecommunications Union (ITU), where the Earth is divided into 15 climatic zones depending on precipitation; R values that are exceeded for different periods of time during the year are shown. This information can be used to determine the availability of a radio channel [4].

B. Fog and Clouds

The rain principle can be applied to take into account many more, smaller droplets. The effect of fog on wireless signal reception is dependent on the operating frequency range. It is not a significant factor below 2 Gigahertz (GHz) range, however, above that threshold, fog can seriously scatter the signal. Talking about cell signal, some of the latest 4G LTE bands operate exactly at those sensitive frequencies.

C. Snow

Ice crystals are far less dense than liquid water, especially in the snowflake form, that is why they do not have nearly the same effect on signal propagation. It is evident that very heavy snow may still refract radio waves, reducing signal strength significantly.

D. Water

The high frequency wavelengths used by phones do not travel well through water. Because water conducts electricity, it can reflect radio waves as well. Water vapor absorbs the energy of radio signals, which is later transformed into heat – effect is similar to the microwave oven operation. Basically, water blocks the radio signal between the tower and reception device.

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There are no or few obstructions to radio signals traveling across bodies of water, and cool water temperatures can create surface inversions that trap a layer of cool air close to the surface. Both factors together may mean longer than usual reception ranges between two points separated by a body containing water.

E. Hail

The size and density of the hail are the most important parameterizing factors. Since ice is less dense than water, and hail does not tend to fall as thickly as rain, it means that its refraction of cell signal will be smaller, too.

F. Lightning

The huge charge of a lightning bolt can cause electrical interference and can damage antennas, power sources, and other transmission equipment, however, since lightning is very short in the physical manner, the disturbance on the signal is short as well, meaning the worst-case scenario of negligible increase in communication time.

G. Wind

Wind alone does not interfere with radio signals. But the weather conditions it is associated with, as described here, can. Wind can damage exposed cell towers, power lines, and the electrical equipment associated with them, basically meaning indirect influence on the signal itself.

H. Trees

The dense biomass of a forest contains a lot of water, so the trunks and leaves of trees tend to reflect and absorb radio signals. In a deciduous forest, better reception in winter than in summer may be expected; it is due to the trees shedding their leaves, opening up the space for radio transmissions to pass through [5].

A portion of the WLL (Wireless Local Loop) link path can pass through vegetation, mostly through the foliage of tall trees. In some suburban areas and small towns, such barriers will most likely not be eliminated, even by installing antennas on rooftops. The study led to the following conclusions: a) The presence of trees near the location of the subscriber can lead to fading due to multipath propagation; b) The main multipath effects caused by the presence of leaf cover are diffraction and scattering; c) Measurements carried out in the gardens with a periodic structure gave the following results: absorption of 12–20 dB per tree for hardwoods and up to 40 dB for a group of 1–3 conifers when the foliage is within 60 % of the first Fresnel zone; d) The effects of multipath propagation are strongly dependent on wind. Thus, when installing WLL systems for each subscriber, attempts should be made to ensure that there is no foliage in 60% of the first Fresnel zone. However, the presence of trees does not make communication impossible; it simply means that some adequate countermeasures, such as the use of direct error correction schemes, need to be applied [4].

I. Air Temperature

Any observed correlation between signal strength and atmospheric temperature is mostly directly bound to the corresponding changes in humidity levels. The strength of the signal reaching reception device should not be impacted by a temperature change alone. It is also important to understand that the line-of-sight propagation of UHF frequencies differs from the way very low frequencies bounce between the earth and ionosphere, therefore traveling very long distances. Atmospheric conditions that may allow a poorly organized radio operator to bounce their signal to the opposite side of the world will not allow a line-of-sight cellular transmission to extend its range. Temperature inversions, where a layer of warm air is trapped above a layer of cool air (see Fig. 1), create conditions similar to the atmospheric duct that can bounce off radio signals.

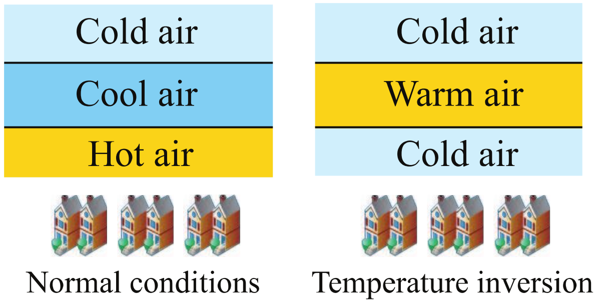

Fig. 1. Pictorial representation of atmospheric duct-like conditions.

While the short waves of UHF signals are not typically reflected, a cell tower located in a layer of clear, cool air that is under a layer of warm, damp air may extend the range of reception.

J. Physical Obstructions

The most common limitation on the reception range is simply the presence of physical obstructions. Because UHF signals are best transmitted on the line-of-sight, i.e. a presence of a mountain between the transmitter and receiver will restrict radio waves from passing by, even on short distances. Tall buildings with lots of metal used in their construction increase signal interference even further [5].

K. Summary

Weather is the state of the atmosphere, to the degree that it is hot or cold, calm or stormy, clear or cloudy. Weather generally refers to day-to-day temperature and precipitation activity. Precipitation is defined as liquid or solid condensation of water vapor falling from clouds or deposited from air onto the ground. Precipitation occurs when a local portion of the atmosphere becomes saturated with water vapor, so that the water condenses and precipitates. The main forms of precipitation include fog, snow, drizzle and rain. Precipitation is measured as the amount of water that reaches horizontal ground or the horizontal ground projection plane of the earth's surface. Precipitation is measured in quantity for a certain time interval, i.e. millimetres per hour, which means that 1-millimeter measure corresponds to 1 litre of water per square meter. All wireless signals that travel from one antenna system to another experience some form of loss. Properly designed systems use the precisely adapted antennas, frequencies, and transmit power to overcome the loss that will take place in the propagation path.

Wireless interference is an important consideration when planning a wireless network. Environmental factors like weather condition, lightning and fog can create interference to the electromagnetic signals. Weather conditions can have a huge impact on wireless signal integrity, even moisture such as fog, rain, and snow add attenuation to the signals path [1]. The amount of attenuation rain can cause depends on the frequency being used for signal transmission. Electromagnetic waves propagate from their source to their destination through a medium, and during the propagation, an electromagnetic wave loses its energy depending on the condition of the medium through which it travels. Anything encountered between a wireless transmitter and receiver can reduce signal strength through attenuation. This not only includes solid objects like walls and doors, but liquid objects as well, like rain and mist. According to the CWNA Study Guide, 2.4 GHz signals may be attenuated by up to 0.05 dB/km by torrential rain or 0.02 dB/km by thick fog. Rain can also reduce signal strength through water accumulation on other objects (trees, leaves, absorbent walls) which contributes to increasing signal attenuation [22].

II. Effects of Weather on the Lifetime of Wireless Sensor Networks Using FSO/RF Communication

A. Approach Applied in Wireless Sensor Network Organization and Power Consumption

When used in outdoor WSN, the FSO/RF hybrid links are the subject to different weather conditions. Among different weather conditions, rain, fog, and snow are known as the most important attenuating factors of optical communications. This motivates considering the most important effects of fog, snow and rain on optical communications applied to long lasting, terrestrial WSN applications [20], [23]. We consider a hybrid WSN topology where the sensors are equipped with both RF and optical interfaces. In particular, for the purpose of our analysis of the effect of fog, rain and snow, we consider a pair of nodes with the potential to communicate on both RF and FSO links. Regarding the alignment and acceptable attenuation, the FSO links are assumed to have reasonable transmission and receiver diameters. However, for the sake of simplicity, we also assume that each sensor can communicate through line-of-sight FSO link with only one other sensor. In our analysis and experiments we assume that the FSO links use the transmission wavelength of 850 nm. The motivations behind selecting this transmission spectrum are the ready commercial availability of Vertical Cavity Surface Emitting Laser (VCSEL) and the presence of high response of silicon photodiodes at this wavelength [7]. Furthermore, we already have available measurements of the attenuation at this wavelength that can be used to analyse the power consumption for rain and snow events. The FSO link consists of VSCEL driver, VCSEL Laser diode, PIN photodiode and corresponding transimpedance and limiting amplifiers. On the other hand, we assume that the RF links are omni-directional and they are based on transceivers compliant with the IEEE 802.15.4 standard. Thus, all nodes are assumed to have RF communication capability with 2.4 GHz carrier frequency and data rate of 250 kbps. Finally, we assume to have a receiver sensitivity of −90 dBm and even less as provided by some commercially available WSN. The sensor nodes can store small amount of energy due to their small size [24]. The energy per bit for FSO communications is set to $1.48 \cdot 10^{-7}$ mJ/bit, whereas energy per bit consumption for RF link is $2.03 \cdot 10^{-4}$ mJ/bit [7]. In the actual communications between a pair of nodes, the nodes use the longest possible FSO link (that ensures the highest energy savings), however, signal attenuation due to fog, rain, or snow requires switching back and forth to RF or FSO. A simple way of such switching consists of using two thresholds on the FSO attenuation: one to switch from FSO to RF (once the signal on the FSO links approaches the limit of its sensibility), and the other to switch from RF to FSO (once the signal on the FSO regains its operation received signal strength). In order to avoid continuously switching back and forth between FSO and RF, the two thresholds are kept separate, organizing hysteresis-like operation. However, switching the RF link takes time that may result in periods of link unavailability, in particular, if the threshold on the optical signal is too low, there may be an interruption in the service because the optical link is unavailable and the RF still needs to be turned on. Considering this fact, we introduce an additional intermediate threshold that is used to turn on the radio (to keep it ready), but to continue using the FSO link, which basically overlap each other. This way the radio is immediately available as soon as the FSO link becomes unavailable. Therefore, our switching schema uses three thresholds on the received signal strength of FSO link. At one threshold level, called RF activation, the RF link is activated but the transmission continues on the optical link. The criterion for selecting FSO link is that the received signal strength should be of the value of 3 dB above the receiver sensitivity to ensure bit error rate in the range of 9^{-10}. The fog measurements that were carried on in Graz (Austria) show that the specific attenuation of the optical link changes at the rate of ±10 dB/km per second in the case of snow events. The corresponding change in specific attenuation for fog events is ±10 dB/km per second. At the second lower threshold level, called RF transmission, the transmission on the optical link is stopped and the transmission on the RF link is started. The third threshold level called FSO Switch back is used to deactivate the RF link and to restart the transmission on the optical wireless link [20].

B. Fog Effects and Measurements

The communication medium strongly influences the propagation of the signal. Generally, atmosphere is the communication medium for terrestrial applications. Among atmospheric effects on FSO, fog is the most detrimental. There are several physical parameters, such as liquid water content, particle size distribution, average particle size, fog temperature, etc., that play an important role in characterization of the fog. The fog causes attenuation at transmission wavelength of optical and near-infrared waves due to scattering and absorption, as the size of fog particles is comparable to these wavelengths. The most accurate way to calculate attenuation in case of fog droplets is based on Mie scattering theory. However, it requires detailed information of fog parameters like particle size, refractive index, particle size distribution, etc., which may not be readily available at a particular location of installation. Moreover, the calculations based on Mie scattering are complex and involve difficult computation. An alternate way is to use the visibility data to predict fog attenuation. The determination of fog attenuation in terms of visibility has been investigated in detail by Kruse [24] and Al Naboulsi [6], [21]. The fog effects on hybrid networks have been investigated and it has been shown that attenuation for RF links below 10 GHz is insignificant. As fog is more crucial for optical wireless communication link, its effects are the focus of analysis. The data used for the analysis were taken in two different measurement campaigns, performed in Graz (Austria). In one measurement campaign, the specific attenuation of FSO was measured in the winter months from the years 2004 to 2005 and 2005 to 2006. The measurements were carried out at a wavelength of 850 nm and 950 nm at a distance of 79.8 m and 650 m, correspondingly. The optical transmitter had two independent LED based light sources, one operating at 850 nm center wavelength and 50 nm spectral width at a full divergence of 2.4 °, which emits 8 mW average optical power; average emitted power in this case after the lens is about 3.5 mW. The second source operated at 950 nm center wavelength and 30 nm spectral widths at a beam divergence of 0.8 ° using four LEDs each emitting 1 mW to produce the same average power at the receiver. The data were collected and sampled at every 1 s. The availability of FSO link reduces drastically due to the fog. The availability of FSO link was measured in another experimental setup for four years from 2000 to 2004. The tested FSO system (MultiLink155F) features a multiple beam system. The distance between the two setup FSO units was 2.7 km. Experiment was arranged so that the PC transmitted two PINGS every minute and recorded the replies [20].

C. Rain Effects on Hybrid Network

When the optical signal passes through the atmosphere, it is randomly attenuated by fog and rain. Since it is known that fog is the main attenuation factor for optical wireless links, the rain attenuation effect cannot be ignored, especially in particular environments where rain is more frequent than fog. As the size of water droplets of rain increases, they become large enough to cause reflection and refraction processes. These droplets cause wavelength independent scattering. It was found that the resulting attenuation increases linearly with the rainfall rate; furthermore, the mean value of the raindrops size is in the order of a few millimetres and it increases with the rainfall rate. Let R to be the rain rate, measured in mm/h, the specific attenuation of wireless optical link is expressed as:

$$a_{\text{spec}} = 1.076 \cdot R^{0.67} [\text{dB/km}]. \tag{1}$$

The most general form of a raindrop size distribution function N_a is given by [20]:

$$N_a = \frac{N_\text{T}}{a_0 V_a} \phi(n) n \left(\frac{a}{a_0}\right)^{n-1} e^{-\phi(n)\left(\frac{a}{a_0}\right)^n}, \quad \text{with } a_0 = d\left(z_a\right)^b e^{-cz_a} \text{ and } \phi(n) = \Gamma^n\left(1+\frac{1}{n}\right), \tag{2}$$

where z_a is the rainfall rate with raindrops of the radius a, measured in millimetres. Typical rainfall parameters are: $d = 0.941$, $b = 0.336$, $c = 0.471 \cdot 10^{-2}$ and $n = 3$ [11]. The overall constant N_T (2) represents the total number of raindrops of all sizes per unit volume. The total rain scattering coefficient is derived from the following equation [11]:

$$\beta_{\text{scat}}^{\text{rain}} = \pi \sum_a a^2 N_a Q_{\text{scat}}\left(\frac{a}{\lambda}\right), \tag{3}$$

where Q_{scat} is the scattering efficiency, which is also referred as the Mie attenuation coefficient. The performance of RF communications in the GHz range is also degraded by rain attenuation which restricts the use of GHz frequencies for line-of-sight communication link. Although the propagation of signals is greatly affected by fog, clouds and dust particles, the rain is the major attenuating factor at frequencies above 10 GHz [8]. The relationship between specific attenuation and rain rate is given by

$$\gamma_\text{R} = kR^\alpha \ \ [\text{dB/km}], \tag{4}$$

where k and α depend upon the frequency and microstructure of rain. The theoretical background of the above relationship is given in [9]. According to ITU-R model, constants k and α in (4) are calculated from:

$$k = \frac{\left(k_\text{H} + k_\text{V} + \left(k_\text{H} - k_\text{V}\right)\cos^2\theta\cos 2\tau\right)}{2}, \quad \alpha = \frac{\left(k_\text{H}\alpha_\text{H} + k_\text{V}\alpha_\text{V} + \left(k_\text{H}\alpha_\text{H} - k_\text{V}\alpha_\text{V}\right)\cos^2\theta\cos 2\tau\right)}{2k}, \tag{5}$$

where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal axis. The values of constants k_H, k_V, α_H and α_V for linear polarization (horizontal and vertical part) are given in [20].

D. Snow Effects on Hybrid Network

The scattering of light occurs due to fog, rain and other precipitations and the received signal strength is reduced as a result of laser beam power attenuation. Consequently, either complete link failure or bit errors are seen when received signal fluctuations are large and received signal level decreases drastically [10]. For the FSO link, the amount of light attenuation increases proportionally to the number and size of fog, rain and snow particles [11]. It is well known that variation in the received signal strength increases with the amount of rainfall [10], [12], [13]. As snowflakes are generally larger than rain drops, the received signal strength fluctuation will be larger for snow and snow attenuation becomes significant [14]. The size of snowflakes as large as 20 mm has been reported [15], [16] and if the laser beam is narrow, a large snowflake can cause link failure. When a snowflake crosses the laser beam, the received signal level depends on the diameter of the snowflake, and on the distance from the transmitter and the position of the snowflake relative to the cross section of the beam [14]. The FSO attenuation due to snow has been classified into dry and wet snow attenuations [17]. If S is the snow rate, measured in mm/h, then specific attenuation in dB/km is given by [17] as:

$$a_{\text{snow}} = aS^b \text{ [dB/km]}. \tag{6}$$

If λ is the wavelength, the parameters a and b for dry snow and wet snow are given in Table I.

TABLE I
SPECIFIC ATTENUATION PARAMETERS FOR DRY AND WET SNOW

Snow type	Parameter a	Parameter b
Dry	$5.42 \cdot 10^{-5} \lambda + 5.4958776$	1.38
Wet	$1.023 \cdot 10^{-4} \lambda + 3.7855466$	0.72

The fog, rain or snow particles also affect the GHz FSO links due to scattering. The calculation of the scattering properties of different hydrometeors involves the knowledge of their dielectric properties. Dielectric properties are usually expressed by the complex dielectric constant or the complex refractive index. Snow particles are the complicated mixtures of ice with air, water, or both. The mixing rate and the shapes of the constituents may vary considerably depending on the external meteorological conditions to which snow particles are exposed. For the theoretical treatment of the electrical properties of such a mixture, it is assumed that the component materials are large enough to be able to assign their dielectric functions. Nevertheless, finding the accurate enough dielectric function of such a mixture is a quite difficult problem since a large number of interactions can occur among the component materials. The solutions can only be obtained by various approximations. The radio wave attenuation due to snow is difficult to analyse as there is a lot of weather dependent variations in shape, dielectric constants and size distribution of snowflakes. It is certain that the attenuation due to dry snow in the microwave region is an order of magnitude less than that due to rain of the same rate of precipitation. However, wet or watery snow gives attenuation comparable to that due to rain in the microwave and millimetre wave regions. Attenuation often exceeds that of rain; attenuation as large as six to seven times the attenuation due to rain was reported in [18]. Measurements made at a wavelength of 0.96 mm have indicated that at this wavelength range the attenuation due to dry snow exceeds by 30 to 40 percent the attenuation due to rain of the same intensity [19]. This indicates that the snow attenuation may be increasingly important as wavelengths get short. The specific snow attenuation A in terms of snow rate R is expressed as [19], [20]:

$$A = 0.00349 \frac{R^{1.6}}{\lambda^4} + 0.00224 \frac{R}{\lambda} \text{ [dB/km]}. \tag{7}$$

E. Results

The reduced link availability of FSO due to weather effects urges to include the attenuation effects of rain and snow in the analysis. Keeping in view the receiver sensitivity and changes in signal attenuation, the optimal usage of power efficient FSO links can be achieved by proper selection of the thresholds. The simulation results for recorded fog, snow and rain events show that the power consumption saving on RF transmissions can be rather significant using a switching schema with three thresholds. Furthermore, the network lifetime in harsh outdoor terrestrial environments is doubled to the case of RF links only. The effect of low energy consumption per bit by FSO links becomes prominent with the increase of throughput [20].

III. IMPACT OF WEATHER CONDITION ON MANET ROUTING PROTOCOLS

Mobile ad-hoc network (MANET) is a dynamically reconfigurable wireless network without any centralized administration or infrastructure. Here each node acts as a router for each of other nodes. Data transmission over a wireless ad-hoc network links in adverse weather condition affects the network performance. Therefore, deployment of MANET during rainstorm or unfavourable environment conditions should pay special attention to the probability of data loss and delay [23].

As mentioned, data transmission over a wireless ad-hoc network links in adverse weather condition affects the network performance. Performance degradation in terms of overall system performance is valid for most popular protocols.

Integrated water resource management system in a municipality could be considered a real-life example of data transmission over a wireless ad-hoc network links in adverse weather condition. Different Automated Reading Metering systems have been used in the last years in Latvia and neighbouring countries, which use smart meters and WSN. The reliability of the monitoring and control systems in municipalities is an important issue, however, very few research projects have been devoted to reliability and resilience to the adverse weather condition.

Basic block scheme (see Fig. 2) represents WSN system that collects and transmits data on water consumption and water temperature at the premises, also water flow and pressure values in the water distribution network [25], [27].

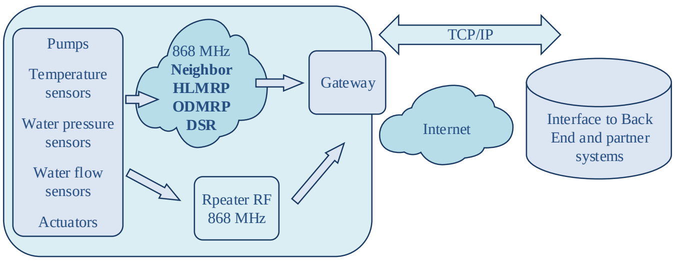

Fig. 2. System architecture of the investigated Wireless Sensor Network.

Basic data flow consists of the sensor itself, which registers and converts analog water flow and pressure signal values to digital ones, then data are processed into messages and are sent to the gateway (concentrator) using Short Range Devices (SRD) ISM unlicensed telemetry band, frequency of 868 MHz, which is the main object of analysis in this paper. Later, the data are forwarded through classic internet network, where they are processed, stored and managed by final user through web interface [26].

A. Simulation Environment

Simulation and analysis using *MATLAB* software package running on Windows 10 x64 machine were performed. MANET simulation toolbox with external routing protocols libraries was used. Ability to substitute real RF sensors and network parameters together with the possibility of further information analysis were the main criteria for selection of such simulation environment. The nature of open source toolbox permits simulation to be tuned close to the real environment.

B. Routing Protocols

Several popular tree and mesh topology-based protocols were used for MANET simulation.

Dynamic Source Routing (DSR) incorporates two mechanisms, Route Maintenance and Route Discovery, while maintaining route caches in the node. Packet sender caches complete ordered route list of the nodes through which packet will be sent to the receiver, the cache is updated as nodes learn new routes. Check of the route is incorporated in the packet's header, and at route failure Route Discovery mechanism is initiated. Verification of route links is performed by querying Acknowledgement (ACK) packets.

Hop Limited Multicast Routing Protocol (HLMRP) uses classical tree-based topology with limited hops available for selecting the route. Nodes presence in the three data is collected through fixed time interval heartbeat messages broadcasted in the network.

1-Hop Neighbor Discovery and Clustering protocol uses the technique of discovering neighbor nodes presence. Node polling is performed by broadcasting advertisement messages, with the corresponding returned packets representing alive node. Neighbor Discovery mechanism is a part of IPv6 standard.

On-Demand Multicast Routing Protocol (ODMRP) is a soft state Mesh based protocol, where a subset of particular nodes performs forwarding of the multicast packets. On-demand driving mode ensures mobility robustness, the whole network topology is not stored dynamically routing the acquired data.

C. Parameters

During the simulation, the packets with data length of 512 bytes with the period of transmission of 100 ms maintaining constant bitrate were sent. Node locations are depicted in Fig. 3.

Simulation time is fixed to 15 seconds. The total of 10 nodes is simulated, 5 of them are data transmitters (indexes 3, 4, 5, 6, 7) and 3 are receivers (indexes 1, 2, 8). The remaining two nodes serve as data transceivers, if they present in the direct path between communicating nodes. The main parameters of the RF network and the sensors were selected considering the characteristics of real hardware. Carrier frequency of 868 MHz was selected because it meets the requirements set for a public band regulated by the norms of the EU, it also meets ERC-REC-70-3E requirements and is widely used by low power technologies, i.e. LoRa and Sigfox [28].

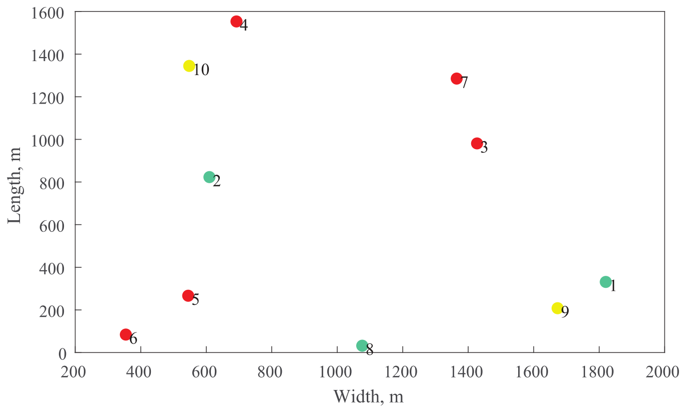

Fig. 3. Visualization of geographic distribution of nodes used in MANET simulation.

Physical network layer is characterized by the parameters obtained from Friis transmission equation:

$$\frac{P_r}{P_t} = \left(\frac{A_r A_t}{d^2 \lambda^2} \right), \quad (8)$$

where P_r and P_t denote power at receiving and transmitting antenna terminals, A_r and A_t – effective aperture of antennas, d represents the distance between antennas, λ denotes the wavelength of the radio frequency. The values used for simulation are presented in Table II.

TABLE II

PHYSICAL PARAMETERS USED IN SIMULATION

Parameter	Value
Carrier frequency, MHz	868
Modulation type	BPSK
Bitrate, Mb/s	10
Transmission power P_t, dBm	20
Receiver sensitivity P_r, dBm	−95
Geographical area W × H, m	2000 × 2000

Modulation, bitrate and power characteristics were derived from industrial sensor characteristics, a square geographical area of average size was selected for the sake of simplicity, as area imperfections are not the main object of the present analysis.

Three different weather disruptions (fog, rain and snow) were applied to four investigated protocols by translating their attenuation equations measured in dBm/km to node positions and physical distance between neighbour nodes.

D. Results

After simulation, analysis of results was performed. Additional simulation of the baseline was carried out, where no disruption values were applied. The results have been taken into account as a reference value for evaluation of sustainability of the protocols. The results of simulation are presented in Fig. 4.

It is evident that baseline (reference) values for all protocols are more or less evenly distributed and are non-zero, which implies that even without disruptions such network is highly loaded and some packet drops occur. With rain attenuation model applied, ODMRP protocol shows the highest number of dropped packets (35.84 %). For dry and wet snow models, all protocols except ODMRP operate with good confidence. HLMRP protocol shows the best performance for this particular environment in terms of number of dropped packets, it has proved to be very sustainable to rain attenuation factors – 8.56 % dropped packets out of the total.

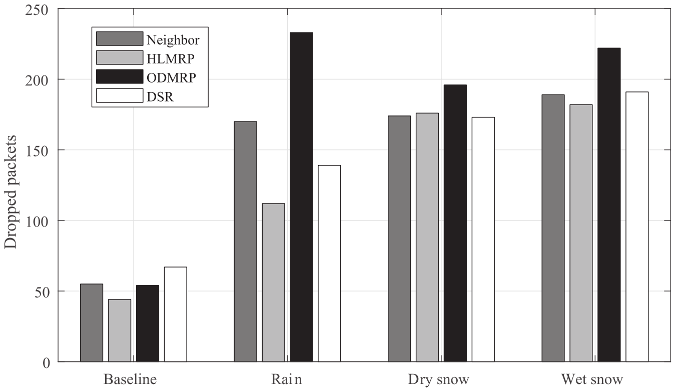

Fig. 4. Dependency of dropped packet value on weather-based disruptions within different protocols and baseline values, lower is better.

However, after the analysis of the overall protocol performance over all disruptions as the ratio of the dropped packets to total sent packets, it is evident that ODMRP protocol demonstrated the best performance. The results, where the average is calculated considering the baseline (no disruptions) value and without it, are provided in Table III.

TABLE III
SUMMARY OF DROPPED PACKETS RATIO PER PROTOCOL OVER ALL DISRUPTIONS

Protocol	Average with baseline, %	Average without baseline, %
Neighbour	37.89	46.01
HLMRP	39.51	40.36
ODMRP	27.09	27.76
DSR	43.37	50.24

Particular weather disruption models, like wet snow, have proved to be the most stressful for all four analysed protocols, whereas dry snow causes a lower impact. The rain model caused the highest distribution between protocols, thus it may be concluded that rain is the most disruptive factor within this particular simulation.

IV. How to Decrease Vulnerability of Wireless Networks From Weather-Based Disruptions

Meteorological conditions significantly affect the signal quality in wireless networks. Most of all, the wireless connection is affected by temperature and solar radiation. Previously it was considered that meteorological conditions did not affect frequencies below 10 GHz, however, taking into account the research data for the last years, it became obvious that factors such as rain, cold, heat, sunlight and other natural factors can significantly change the performance of wireless networks that operate at frequencies up to 2.4 GHz. Research of network parameters from the point of view of telematics can be expedient, as it can allow real-time optimization of the performance of wireless networks [30], thus improving the quality of services received by the end user. The results of such studies can help network developers and researchers to create new protocols – adapted to the climatic characteristics and weather conditions, which will ensure the best performance of wireless networks and optimize their work.

It is therefore proposed to use meteorological weather predictions (see Fig. 5) for respective online configuration of wireless networks. In case of particularly adverse natural phenomena, additional reserve data transmission channels should be set up in advance to assure endurance of wireless networks.

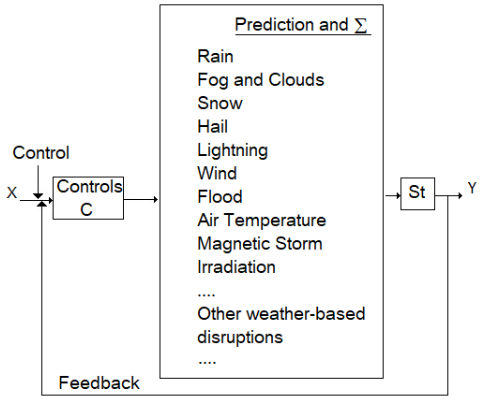

Fig. 5. The use of meteorological weather predictions for online configuration of wireless networks.

Because of the changing climatic conditions in the world, natural disasters and unusual weather conditions are becoming very common in various regions of the planet. Considering the fact that today wireless networks are widely spread, as well as the fact that the uninterrupted operation of wireless networks largely depends on weather conditions, it is important to be able to prepare wireless networks for natural disasters.

Knowing in advance what kinds of environmental conditions are most probable in the designated area provides an opportunity to constrain a wireless network by tuning the necessary parameters for the best performance. In this case, the vulnerability of wireless networks from meteorological failures is considerably reduced. Preparation implies real-time selection of the suitable protocols and wireless communication standards that are most suitable for such type of weather conditions.

V. Conclusions

It is significant to predict correctly weather-based disruptions and configure wireless networks online and beforehand.

Simulation results have proved that it is necessary to select the most suitable protocol according to common weather conditions in the designated wireless network environment.

It is therefore proposed to use meteorological weather predictions for online configuration of wireless networks accordingly. In case of particularly adverse natural phenomena, additional reserve data transmission channels should be set up in advance to increase the stability of municipal wireless networks [29].

The experimental simulation has shown that ODMRP protocol demonstrates the highest number of the dropped packets, but it still results in the best performance over all weather disruptions in terms of the ratio of dropped packets – 27.76 %, because it allows the highest number of packets to be transmitted over the same execution time.

Application of online methods of configuration in combination with prediction system ensures that a wireless network is stable and is immune to weather-based disruptions.

The results of the research may be useful for the specialists, who develop integrated water resource management systems in municipalities and for the next generation of technologies [31].

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