ABSTRACT
The idea of multi-hop communication originates from the 1990’s and is eagerly incorporated in the wireless sensor network research field, since a tremendous amount of energy can be saved by letting —often battery powered— nodes in the network assist each other in forwarding packets. In such systems it is key-issue that the wireless medium is spatially reused. The lightweight medium access control (LMAC) protocol relies for spatial medium reuse on the following assumption [1]: a receiving node can distinguish whether an erroneous packet is caused by an (concurrent) interfering transmissions or due to e.g. noise.

In this paper this assumption is verified by path loss and interference measurements. Both outdoor (pasture land) and indoor (corridor) measurements were conducted.

From the results it can be concluded that there is a sharp defined communication range. And that packet errors within this range can be attributed to interferers that are within interference range.

1. INTRODUCTION
The network diameter of wireless sensor networks (WSNs) is expected to be larger than the transmission and interference ranges of the individual wireless sensors. WSNs are thus assumed to be multi-hop networks, which allows for spatial reuse of the wireless medium. Obviously, this is beneficial for the network, because more data can be transported per second per meter (i.e. higher transport capacity) [2].

In [1], we presented the LMAC protocol that targets especially energy-efficiency, self-configuration and distributed operation. The LMAC protocol is based upon scheduled access. Each node gets periodically a time interval in which it is allowed to control the wireless medium according its own requirements and needs. Outside this interval, nodes are notified when they are intended receivers. When a node is not needed for communication, it switches its transceiver to standby and is hence able to conserve energy. Since each node gets its own turn in using the medium, there will be little collision of messages which is in other types of MAC methods — such as carrier sense multiple access (CSMA)— one of the main reasons for energy waste [3]. The LMAC protocol is shortly discussed in Section 2.

In this document, two research questions are investigated. First is it possible to spatially reuse the wireless medium. Second, if the medium is reused, can collisions be detected. For example can nodes distinguish between bit errors and overlapping transmissions?

These research goals are studied by measurements on the nodes described in [4]. These nodes operate in the 868 MHz Industrial Scientific and Medical (ISM) band. With use of path loss measurements the first objective is analyzed. Because the results will be compared with deterministic models, measurements were conducted in simple geometric environments: a pasture land (outdoor) and two corridors (indoor). With interference measurements collisions are introduced. Based on the results the second question is evaluated.

The organization of this paper is as follows. In Section 2 the LMAC protocol is presented. Section 3 deals with models to describe the indoor and outdoor path loss. Resulting in an expected maximal communication and interference range. The experiment setup and actual measurements are discussed in Section 4. This paper concludes with reflections on the before mentioned research goals.

2. THE LIGHTWEIGHT MEDIUM ACCESS PROTOCOL (LMAC) FOR WSNs
In schedule-based MAC protocols, time is organized in time slots, which are grouped into frames. Each frame has a fixed length of a (integer) number of time slots. The number of time slots in a frame should be adapted to the expected network node density or system requirements. The scheduling principle in the LMAC protocol [1] is very simple: every node gets to control one time slot in every frame to carry out its transmission. When a node has some
Figure 1: Time slot contents of the LMAC protocol. The data message (DM) does not have a fixed length and is even omitted when a node does not have any message to send.

data to transmit, it waits until its time slot comes up, addresses a neighboring node (or multiple) and transmits the packet without causing collision or interference to other transmissions.

In order to be capable of receiving messages, other nodes always listen at the beginning of time slots of other nodes to find out whether they are addressed either by node ID or by broadcast address.

In the LMAC protocol, a time slot is divided into two parts of unequal length (Figure 1): control message (CM) and data message (DM). A node always starts its time slot by sending out a CM, even if it does not have any data to send. Besides addressing other nodes, the CM is also necessary for synchronization, resolving collisions and the operation of the distributed time slot scheduling.

In [1], we address the distributed time scheduling mechanism of LMAC. MAC protocols, build upon the handshaking mechanism proposed by Bharghavan et al. [5], prevent nodes to use the wireless medium when it would disturb ongoing communications. The handshaking mechanism of these contention-based MAC protocols consists of two steps: (1) reservation of the medium by the transmitting node and (2) reservation by the receiving node.

In step (1), the medium is reserved by the RTS message and all nodes in range of the transmitter postpone transmissions. In step (2), the receiver replies with a CTS message and all nodes –able to receive this message- postpone their transmissions. In [1], we propose a similar solution for medium reservation in the schedule-based LMAC protocol. In our solution, nodes determine what time slots are available for use and what time slots interfere other nodes. We require each node to transmit at least once during its controlled time slot. By this we make sure that all nodes in radio range are aware of the node, comparable to the reservation of the medium of the transmitting node (RTS) in the above described handshaking mechanism.

Additionally, nodes transmit a list (i.e. bit vector) of already used time slots of first order neighbours in their CM. This is comparable to CTS messages. A newly joined node collects time slot usage information during one complete frame. After this information is collected, it can compile a set of time slots, which are not in use by its neighbour nodes or the neighbours of its neighbours (the groups might overlap). From this list any slot can be chosen as controlled time slot without causing collision to any other transmission.

3. PROPAGATION MODELS

Successful reception of a radio signal dependents among others on the received signal strength. Fading influences the received signal strength. Fading can be divided into small-scale and large-scale fading [6]. Large-scale fading are fluctuations in the received power over large distances and/or long times. Path loss and shadowing can be causes of large scale fading. Small-scale fading are fluctuations over small distances (less than $\lambda$) and/or short times (order of seconds). In the subsequent sections large-fading such as path loss is described. Small-scale fading is not considered in this paper.

3.1. Free space path loss

The free space transmission loss can be calculated with use of the Friis transmission formula (Equation 1).

$$P_r = P_t G_t G_r \left( \frac{\lambda}{4 \pi r} \right)^2$$  (1)

With $P_r$ the received signal power, $P_t$ the power of the transmitter and $G_t$ and $G_r$ the gain of the transmitter and receiver, respectively. (Measurements in this paper were conducted at 868.4 MHz, resulting in a $\lambda$ of 0.345 m). When the distance $r$ (between transmitter and receiver) doubles, the power received decreases with 6 dB. For each decade of distance the power decreases with 20 dB.

3.2. Plane earth two ray reflection model

Equation 1 can be extended to account for ground reflection.

The direct line-of-sight wave can be amplified or attenuated by the wave that is reflected by the earth (Figure 2). Path lengths are given in Equation 2.
The path loss can be expressed as Equation 3 [7].

\[
P_r = P_t G_t G_r \left( \frac{\lambda}{4\pi r} \right)^2 \left[ 1 + R e^{i\Delta} \right]^2
\]  

(3)

Where \( R \) is the reflection coefficient as described in Subsection 3.4 and \( \Delta \) is the difference between indirect path \( r_2 \) and direct path \( r_1 \).

In this model it is assumed that the earth is flat, which is acceptable for small communication ranges. Furthermore the surface wave is neglected. When the ground is rough, scattering occurs. This scattering spreads the energy of the reflected wave.

### 3.3. Indoor ray model

For a corridor the plane earth model can be extended to account for the wall reflections (normal reflection coefficient) and floor, ceiling and back wall reflection (parallel reflection coefficient).

### 3.4. Reflection coefficient

The relation between the amplitude of the reflected and refracted wave (relative to the incident wave) is given by Fresnel’s reflection and transmission coefficients. The reflection coefficients are given in Equation 4 and Equation 5 when the electric field is parallel or perpendicular to the scattering plane, respectively [8].

\[
R_\parallel = \frac{E_\parallel}{E_{\parallel i}} = \frac{n_2 \cos \theta_i - n_1 \cos \theta_i}{n_2 \cos \theta_i + n_1 \cos \theta_i}
\]  

(4)

\[
R_\perp = \frac{E_\perp}{E_{\perp i}} = \frac{n_1 \cos \theta_i - n_2 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_i}
\]  

(5)

The scattering plane is defined as the plane containing both incident and reflected ray. Angles of incidence, reflection and refraction are measured relative to the normal. Equation 6 denotes the formula for the index of refraction of a material.

\[
n = \frac{c}{v} = \frac{\sqrt{\mu_0 \varepsilon_0}}{\mu \varepsilon_0}
\]  

(6)

Where \( \varepsilon_0 = 8.854 \times 10^{-12} \) \( F m^{-1} \) and \( \mu_0 = 4\pi \times 10^{-7} \) \( H m^{-1} \). For a finitely-conducting dielectric the permittivity is complex and may written as Equation 7 [9].

\[
\epsilon = \epsilon_0 \epsilon_r - j \frac{\sigma}{\omega}
\]  

(7)

The angle of reflection and refraction follow from Snell’s laws, shown in Equation 8 and 9.

\[
\theta_i = \theta_r
\]  

(8)

\[
\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1}
\]  

(9)

Some typical constitutive parameters are given in Table 1 and Table 2 [9].

<table>
<thead>
<tr>
<th>Surface</th>
<th>Conductivity ( \sigma ) [S/m]</th>
<th>Relative permittivity ( \epsilon_r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry ground</td>
<td>0.001</td>
<td>4-7</td>
</tr>
<tr>
<td>Average ground</td>
<td>0.005</td>
<td>15</td>
</tr>
<tr>
<td>Wet ground</td>
<td>0.02</td>
<td>25-30</td>
</tr>
<tr>
<td>Sea water</td>
<td>5</td>
<td>81</td>
</tr>
<tr>
<td>Fresh water</td>
<td>0.01</td>
<td>81</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface</th>
<th>Conductivity ( \sigma ) [S/m]</th>
<th>Relative permittivity ( \epsilon_r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry concrete</td>
<td>0.7</td>
<td>5</td>
</tr>
<tr>
<td>Gypsum board</td>
<td>0.15</td>
<td>2.8</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.21</td>
<td>2.88</td>
</tr>
<tr>
<td>Brick wall</td>
<td>0.11</td>
<td>3.3</td>
</tr>
<tr>
<td>Glass</td>
<td>( 10^{-12} )</td>
<td>4-10</td>
</tr>
</tbody>
</table>

For large distances (compared to the antenna heights) the angle of incidence is close to grazing and the reflection coefficient approaches -1 for both parallel and perpendicular polarization.

### 3.5. Empirical path loss models

Objects in the path cause additional losses. Table 3 [12] summarizes some typical losses.

<table>
<thead>
<tr>
<th>Object</th>
<th>Typical loss [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall (indoor)</td>
<td>10-15</td>
</tr>
<tr>
<td>Wall (exterior)</td>
<td>2-38 (percentage of windows and height important)</td>
</tr>
<tr>
<td>Floor</td>
<td>12-27</td>
</tr>
<tr>
<td>Window</td>
<td>2-30 (metal tinted windows cause high loss)</td>
</tr>
</tbody>
</table>

When there are more reflecting and scattering surfaces, determining the path loss becomes more complex. In that
case empirical models can be used to predict the path loss. For outdoor macrocells two possible models for 900 MHz are the Okumura-Hata model and the Lee model. However, these models assume large TX-RX distance (≥ 1 km). For microcells most models are based on the dual-slope model (like the plane earth model).

A model for indoor path loss is given in Equation 10 [13].

\[ L = 20 \log f + N \log d + L_f - 28 \]  

Where \( f \) is the frequency in MHz, \( d \) the distance (transmit-receiver). \( L_f \) and \( N \) are given in Table 4 [13].

Table 4: Distance and floor loss factors for indoor office at 900 MHz [13].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Loss [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>distance power loss coefficient</td>
</tr>
<tr>
<td></td>
<td>floor penetration loss factor</td>
</tr>
<tr>
<td>L_f</td>
<td>18 (corridor)</td>
</tr>
<tr>
<td></td>
<td>24 (three floors)</td>
</tr>
</tbody>
</table>

3.6. Polarization loss

Another additional loss can be caused by polarization mismatch. This loss can be taken into account by the polarization loss factor, defined in Equation 11. [14]

\[ PLF = \left| \cos \psi_p \right|^2 \]  

Where \( \psi_p \) is the angle between the transmitting and receiving antenna. When both antennas are aligned the PLF is 1.

3.7. Expected communication range

Figure 3 shows a schematic of a wireless communication system [7]. Table 5 summarizes the relevant parameters for the path loss measurements.

Gain parameters were estimated based on antenna simulations. The path loss \( L \) can be calculated with the free-space or plane earth reflection model. The received power (which should be > -100 dBm for 0.1% BER) is given in Equation 12.

\[ P_R = P_T + G_T + L + G_R + ML_R + L_R + L_D \]  

With \( L_D \) compensation for the duty cycle of the transmitter. A plot of the received signal strength based on previous described models is shown in Figure 6. The plane earth model shows a clear dual slope. Starting with -6 dB/octave and after the breakpoint (around 30 m) -12 dB/octave (-40 dB/decade). When Equation 12 is calculated with the parameters of two \( \mu \)Nodes then the free space model predicts a communication range of 1098 m. The plane earth model estimates a range of 275 m which seems more realistic. When the indoor models for a corridor are evaluated, the six ray model predicts a communication range of 2790 m and the empirical model a range of 2346 m. Which is perhaps a little bit too optimistic. The expected ranges will be compared with measured communication ranges in Section 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transmitter (( \mu )Node)</th>
<th>Receiver (FSH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>-10 dBm</td>
<td>&gt; -100 dBm</td>
</tr>
<tr>
<td>Feeder loss</td>
<td>-</td>
<td>-1.353 dB</td>
</tr>
<tr>
<td>Gain</td>
<td>1.39 dBi (est.)</td>
<td>2.15 dBi (est.)</td>
</tr>
<tr>
<td>Matching loss</td>
<td>-</td>
<td>-1.73×10^{-3} dB</td>
</tr>
<tr>
<td>PLF</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

3.8. Expected interference range

Correct demodulation by the nRF905 transceiver is only possible if the wanted signal is 13 dB [15] stronger than unwanted signals in the same frequency band (Co-Channel Rejection CCR). Figure 4 depicts one receiver and two transmitters at the same frequency [12]. If \( TX_1 \) transmits the wanted signal and \( TX_2 \) acts as an interferer then the inequality in Equation 13 must hold [12].

\[ (P_{out1} + G_{T1} + G_R - Pathloss_1) - (P_{out2} + G_{T2} + G_R - Pathloss_2) \geq CCR \]  

When the transmitters have equal antenna gains and the path loss is approximated by the free space loss then Equation 13 reduces to Equation 14.

\[ P_{out1} - P_{out2} + 20 \log_{10} \left( \frac{range_2}{range_1} \right) \geq CCR \]  

Thus when two \( \mu \)Nodes transmit with equal output power, the range ratio between them should be at least 4.47 in
order for the receiver to be able to demodulate the signal of the \( \mu \)Node that is closest. For the corridor setup the ratio would be 5.27 (based on the empirical model Equation 10). The actual ratios will probably be smaller for larger distances. Because the path loss falls off more steep for larger distances. In Section 4 the experimental obtained ratios are presented.

4. EXPERIMENT SETUP

RF power measurements were carried out with the FSH-6 spectrum analyzer (manufactured by Rohde-Schwartz [16]) connected to a vertical monopole wire antenna by 2 meter coax cable. This resulted in a VSWR of 1.0407 (matching loss of \(-1.73 \times 10^{-3} \) dB) for the range 840-880 MHz. The FSH was placed on a small furniture trolley. A shelf was mounted to the trolley which holds a vertical stick on which the antenna could be attached. In this way the distance between the antenna and the person operating the FSH was at least 1.5 meter. For the Packet Error Rate (PER) measurements a LCD display was connected to the receiving \( \mu \)Node to display the number of packets that were received correctly in a certain time interval. Measurement locations are shown in Table 6.

<table>
<thead>
<tr>
<th>Table 6: Measurement locations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture land</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Width</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Level</td>
</tr>
<tr>
<td>Floor</td>
</tr>
<tr>
<td>Ceiling</td>
</tr>
</tbody>
</table>

The small corridor contained a lot of reflecting objects, in contrast to the large corridor which was practically empty.

4.1. Path loss measurements

Figure 5 shows a schematic of the setup used for the path loss measurements.

4.1.1. Outdoor

Figure 6 shows the expected path loss including the measured (outdoor) values. For this measurement the \( \mu \)Node was programmed to transmit a (32 bytes) burst in a loop at -10 dBm. The calculated graph was compensated (by -0.7463 dB) for this duty-cycle (84.21 %). The FSH connected to the wire monopole antenna was used as receiver. After 140 m reliable power measurements were no longer possible because the signal was no longer distinguishable from the noise by the FSH. This explains the horizontal tray (noise level -86.3 dBm) at the end of the measured curve. The mean difference between expected and measured values is 4.8 dBm with a maximum difference of 10.5 dBm. The general curvature of the measured and calculated plot match. However it seems that the measured plot is shifted to the left. This is probably due to the fact that the calculated curve is strongly dependent on the height of both transmitter and receiver (FSH). Although the height was set to 1.38 m for both transmitter and receiver, it is possible that due to grass or curvature of the ground the physical height was smaller. In that case the measured and calculated plot are more aligned.

The fact that the measured curve lies systematically lower
than the calculated one suggests that the assumptions made in Table 5 are too optimistic or that an additional loss-factor is overlooked. For instance it is plausible that the gain of the transmitting μNode antenna (1.39 dBi) is lower than estimated. Furthermore the output power, on which the calculated curve is based (-10 dBm), is also only an estimate. According to the datasheet the real value can lie between -6 and -14 dBm. If we take these uncertainties into consideration, it can be concluded that the measured curve agrees reasonably well with the expected curve. And the expected communication range (intersection with the receiver sensitivity at -100 dBm) lies between 250 and 300 m. This was checked by PER measurements.

For these measurements the FSH was replaced by an μNode equipped with a LCD display to display the PER. For a transmitter and receiver height of 1.38 m (on a sand road) the results are shown in Figure 7.

It appeared that the communication range is strongly dependent on the height of the μNode above the ground. For 3λ (1.04 m) and higher the communication range seemed to be almost constant. When the μNodes were placed on the ground, the communication range was strongly reduced. In the transition part (from low packet loss to high packet loss) the data points show a large spread (this region increased for lower antenna heights). For 1.38 m the experimentally observed communication range is 250 m, which corresponds to the expected range. The small difference can be explained by the difference in antenna gains of the μNode (estimated on 1.39 dBi) and the wire monopole (2.15 dBi) used to obtain the received power measurements.

4.1.2. Indoor

The path loss measurement was repeated for the two indoor locations (two different corridors). Figure 8 and Figure 10 shows the plans of the corridors. The red line and crosses denote the line of sight (LOS) and non line of sight (NLOS) measurement positions, respectively. Results of the measurements are shown in Figure 9 and Figure 11. The large corridor contains two passages (at 32.95 m and 79.57 m) which are half-way covert with wired glass. Because they are placed oppositely with respect to each other there was no longer a LOS path after 79.57 m.

In Figure 9 and Figure 11 one measurement series is compared with the models described in Section 3. The empirical model describes the trend of the received power graph reasonably well. Although the slope is less steep (less than -18 dB/decade). The reflection model seems to describe the location of the deep fades rather well, however lies about 5-10 dB too high. In the reflection model, reflections by the end of the corridor are not taken into account. For the small corridor this could sort some effect. Of course the model is only a rough estimation as only first order reflections are considered. Also diffraction and surface scattering are not regarded. After 100 m, in the large corridor, the PER started to decline.

4.2. Interference measurements

Collisions were introduced by using an interferer, scenario Figure 12. One transmitter continuously transmits data...
bursts of 32 bytes at -10 dBm addressed to an µNode programmed as receiver. Another µNode was set into retransmit mode to act as an interferer (also at -10 dBm). This interferer does not address the receiver.

4.2.1. Outdoor

In Figure 13 a typical measurement is shown of the number of correct received packets versus the distance receiver interferer. The distance transmitter receiver was 10.00 m and all the µNodes were placed 1.38 m above ground. In Figure 14 the expected signal difference between transmitter and interferer is plotted. The horizontal line depicts the co-channel rejection (CCR) of the nRF905 transceiver (13 dB [15]).

A clear peak stands out at 12 m. This peak is also present in Figure 14 for the plane earth model (with R approximated by -1). It is possible that at that point the signal of the interferer is strongly attenuated by ground reflection. However the plane earth model with complex reflection coefficient doesn’t show a peak above CCR level. (Note that the plane earth model with R = -1 is an approximation which only holds for gazing angles.) The difference signal interferer strength depends on transmitter, receiver and interferer height. When the height of the interferer is increased the attenuation point shifts.

An interesting case is the situation where the receiver is at the edge of the communication range of the transmitter. For a setup at a sand road this appeared to be 175 meter.

4.2.2. Indoor

A typical indoor measurement is shown in Figure 16. Transmitter, receiver and interferer were all located 1.38 m above ground. The interference range is roughly a factor 4. More peaks are visible than for the outdoor measurements (Figure 13, because there are more reflecting surfaces in the corridor.

4.2.3. Results

Results of the packet interference measurements are summarized in Table 7.

In general, the RX-IX TX-RX ratio is smaller than expected (Section 3.8) from the free space propagation model (outdoor) and the empirical path loss model (indoor). This is due to the steeper decline of signal power for larger receiver interferer distances than the models assume (Figure 6 and Figure 11). Which causes the transmitter interferer signal difference reach the CCR for shorter RX-IX ranges. Resulting in a lower interference range.

Figure 10: Plan large corridor.

Figure 11: Measured received power versus distance with path loss models, large corridor ($V_{bat,TX} = 3.04$ V).

Figure 12: Interference measurement setup.

Figure 13: Received packets versus distance RX-IX, outdoor, distance TX-RX = 10 m ($V_{bat,TX} = 2.96$ V, $V_{bat,RX} = 3.07$ V, $V_{bat,IX} = 3.08$ V).

Figure 15 shows the results. The interference range is in this case much smaller than expected. At the end of the communication range, the reception was extremely sensitive to changes in the environment. For example when a car drove by, the PER was strongly reduced, although there was still a line of sight path present.
From the results we conclude the following. If the received signal strength of the wanted signal is larger than a certain level (e.g. defined by the sensitivity of the receiver), which was the case for the interference measurements presented here, then packet errors can be attributed to collisions caused by interferers. With the interferers within the interference range. However, the reverse is not necessarily true. If communication is possible, there can still be an interferer present within the interference range. Because its signal can be attenuated by reflections as shown in and Figure 13 and Figure 16.

The measured outdoor communication range is in close agreement with the expected communication range. Based on the plane earth model a range of 275 m was expected. Power measurements and PER measurements resulted in a range of 250 m. For the corridors however, the difference between model and measured path loss is larger. This is due (amongst others) to the stronger decline of the signal, caused by the metal tinted windows in the large corridor. Path loss and PER measurements versus transmitter receiver distance show that there is a sharp transition between a low PER and a high PER i.e. no communication possible (provided that the nodes are placed sufficiently high above the ground). If this maximum range is known, and a transmitter and receiver are within this range but experience packet loss, it is likely that there is an interferer within interference range (Table 7). Measurements showed that these interference factors are dependant on the distance TX-RX, the height and height difference between.
between transmitter, receiver and interferer. Therefore it can be concluded that, if the diameter of the WSN is larger than the communication range of the nodes, the wireless medium can be spatially reused, when concurrent transmissions are (1) separated by a distance larger than the interference range or (2) detected as collisions. Nodes can detect collisions based on the received signal strength, the expected communication range and the fact that a packet is received incorrectly.

6. REFERENCES


