# Performance Measurements of Motes Sensor Networks

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## ABSTRACT

In this paper we investigate the performance of mica2 and mica2dot Berkeley motes by means of an extensive experimental analysis. This study is aimed at analyzing the main elements that characterize the performance of a sensor network, e.g., power consumption in different operating conditions, impact of weather conditions, interference between neighboring nodes, etc. Even if the analysis is related to a specific technology it provides some general useful information. Specifically, we found that the transmission range of mote sensor nodes decreases significantly in the presence of fog or rain. We also investigated the interference between neighboring nodes and, based on the experimental results, we propose a channel model for mote sensor nodes. This model is very similar to the channel model of IEEE 802.11 networks.

## Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless communication.* C.4 [**Performance of System**]: Performance Attributes.

## General Terms

Measurements, Performance, Experimentation.

## Keywords

Mica Motes, Sensor Networks.

## 1. INTRODUCTION

The increasing miniaturization of electronic components and the advances in wireless technologies has fostered researches on sensor networks and systems. Individual sensor nodes are low-power devices that integrate computing, wireless communication, and sensing capabilities. They are able to sense physical environmental information such as temperature, humidity, light intensity, etc., and to process these information locally, or send it to one or more collection points (usually referred to as sinks) typically through wireless communications. In important application scenarios a massive deployment of sensor nodes is required, in the order of thousands or tens of thousands. The aggregation of such a multitude of sensor nodes into a computing and communication infrastructure forms what is called a sensor network. Potential applications of sensor networks includes a large number of fields ranging from military, to scientific, to industrial, to health-care, to domestic, etc.

Sensor nodes forming a sensor network are densely (and randomly) deployed inside the area in which a phenomenon is being monitored. Each sensor node delivers the collected data to one (or more) neighbor node, one hop away. By following a multi-hop communication paradigm data are routed to the sink and through this to the users. Therefore, multi-hop ad hoc techniques constitute the basis also for wireless sensor networks. However, the special constraints imposed by the unique characteristics of sensing devices, and by the application requirements, make solutions designed for multi-hop wireless networks generally not suitable for sensor networks [1].

Research activities on sensor networks have mainly focused on networking protocols [1, 11, 15, 17, 18, 19], topology control [16, 20], time synchronization [8], data management [12], security, etc. Special attention has been devoted to study energy-efficient solutions [14] (energy is a very critical factors in sensor networks since individual sensor nodes have a non-renewable power supply and, once deployed, must work unattended). Most of these proposals have been evaluated/validated through extensive simulation analysis [11, 15, 17, 18, 19]. Generally, these simulation studies are based on the ns-2 tool [13] and assumes the IEEE 802.11 CSMA/CA protocol [10] to characterize the physical and data link layers. One may argue whether this modeling provides an accurate characterization of a real sensor network. The aim of this paper is to exploit measurements on a real testbed to answer the above question. To this end hereafter we will investigate whether the IEEE 802.11 model provides an adequate characterization of sensor networks lower layers. If this is true we wish to investigate the correct model parameter setting. Specifically, we intend to investigate the main elements that characterize the sensor network performance, e.g., impact of weather conditions on the transmission range, energy consumption in different conditions, etc.

In this paper we present the results of an extensive measurement campaign. Specifically we used mica2 and mica2dot Berkeley motes and considered different scenarios and traffic conditions. To investigate the impact of environmental conditions on the performance of sensor nodes the experiments were done in an outdoor environment under various atmospheric conditions. Though the analysis is related to a specific technology (i.e., Berkeley motes) we think that the results obtained still provide general useful information. Specifically, we found that the atmospheric environment (e.g., fog or rain) may have a severe impact of the transmission range of sensor nodes. This is very


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important since sensor networks are expected to work in changing atmospheric conditions. Furthermore, based on our experimental results we derived a channel model for the CSMA/CA-based MAC (Medium Access Control) protocol used in our sensor devices. We found that this channel model is very similar to the IEEE 802.11 channel model we derived in a previous paper [2]. Our findings prove that, modeling the lower layer of a sensor network as an IEEE 802.11 network can be considered acceptable as far as the channel model.

The rest of the paper is organized as follows. Section 2 provides a brief overview of the Berkeley motes technology. Section 3 describes the environment and methodology used in our experimental analysis. Section 4 is devoted to the discussion of the experimental results, while Section 5 describes the channel model we derived. Finally, Section 6 concludes the paper.

## 2. BERKELEY MOTES

Berkeley motes sensor nodes [3] are so called because they were developed at the University of California at Berkeley. They come in two different flavors, *mica2* and *mica2dot*, that have similar characteristics but a different form-factor.

Both mica2 and mica2dot sensor nodes have a 4-Mhz, 8-bit Atmel microprocessor (that can be put in “power down mode” to save energy [4, 5]) and 512 KB of non-volatile flash memory that can be used for logging and data collection. Also, they both have a 32-KHz clock that can be synchronized by the operating system to the clock of neighboring sensor nodes with an accuracy of approximately +/- 1 ms. This allows neighbors to be powered up and listen to when there is information to be exchanged between them.

Motes are powered by the TinyOS operating system [6, 7] that is specifically tailored to this type of devices. The design of TinyOS is based on the specific sensor network characteristics, i.e., small physical size, low-power consumption, concurrency-intensive operations, multiple flows, limited physical parallelism and controller hierarchy, diversity in design and usage, and robust operations to facilitate the development of reliable distributed applications. TinyOS follows an *event model* approach instead of a stack-based threaded approach. The latter would have required more stack space and multi-tasking support for context switching.

Motes can host a variety of sensors. A non exhaustive list includes sensors for light intensity, surface and ambient temperature, acceleration, magnetic field, voltage, current (DC and AC), sound volume, ultrasound, barometric pressure, humidity, and solar radiation.

For wireless communication motes use an RFM ChipCon radio that provides a nominal bit rate of 19.2 Kbps by using a CSMA/CA (Carrier Sense Multiple Access, Collision Avoidance) MAC protocol [19]. Similarly to other wireless network interfaces [10] the ChipCon radio is half-duplex and hence the motes sensor nodes cannot detect collisions while transmitting. Therefore, they try to avoid collisions by listening to the channel before start transmitting, and backing off for a random time when the channel itself is found to be busy. The wireless interface can be in one of the following operating modes: *Transmit*, *Receive*, *Idle*, *Sleep* (off). Since, the power consumption in the Sleep mode is significantly lower than in the Idle Mode, it is extremely important to put the radio in the Sleep mode (rather than transitioning to Idle mode) when there are not data to transmit or receive.

The MAC protocol works as follows [19]. Upon receiving a frame to transmit the sensor node generates a random `Initial_backoff` interval, uniformly distributed in the range [15, 68.3] ms, and starts a timer. Then, it enters a loop in which it performs the following actions. Upon timer expiration the channel is sensed. If it is found idle and no incoming frame is detected the frame is transmitted. On the hand, if the channel is found busy the sensor node generates a further random time interval (`congestion_backoff`), uniformly distributed in the range [12.08, 193.3] ms, and starts the backoff timer again. The above actions are repeated until the channel is found free and the frame is thus transmitted.

Please note that the MAC protocol does not include any mechanism to detect collisions (e.g., ACK frames as in the IEEE 802.11).

```
Initial_backoff = rand(15ms,68.3ms);
SMacDelay = Initial_backoff
Start_Timer(sMacDelay);
Repeat{
  Upon timer expiration do{
    if(not (received_preamble() and
     busy_channel()))
    then{
      transmit the frame;
      exit();
    }
    else{
      congestion_backoff =
     rand(12.08ms,193.3ms);
      sMacdelay = Congestion_backoff
      start_Timer(sMacDelay)
    }
  }
}
forever;
```

**Figure 1. A pseudo-code description of the CSMA/CA protocol used in the motes.**

## 3. EXPERIMENTAL ENVIRONMENT

We now briefly describe the methodology we used in our analysis. In our experiments we used either mica2 or mica2dot sensor nodes. We performed a large set of experiments involving various scenarios and different numbers of sensor nodes. Each experiment was replicated 10 times in the same day or in different days, with consecutive replicas separated by at least five minutes to run out possible electromagnetic phenomena that could affect the experiment’s results. For performance measure we derived both the average value over all replicas and lower and upper bounds.

To compensate the lower performance exhibited by *mica2* in radio transmissions we used a system called *virtual ground* to improve measurements’ precision. Each sensor has a small copper table so that the antenna sees an equipotential surface as ground, and it behaves like a dipole because of reflections. When using the virtual ground the transmission channel is more homogeneous since it limits reflection’s phenomena and bad electromagnetic wave’s perturbation.

Finally, to measure the relative humidity we used a *hygrometer*, while to measure the rain intensity we used a *pluviometer*.

To better understand the results presented in the next session, it may be worthwhile to provide a model of the relationships existing among sensor nodes when they transmit or receive. In particular, it is useful to make a distinction between the transmission range and the carrier sensing range. The following definitions can be given.

- The *Transmission Range* (*TX_range*) is the range (with respect to the transmitting sensor node) within which a transmitted frame can be successfully received. The transmission range is mainly determined by the transmission power and the radio propagation properties.
- The *Carrier Sensing Range* (*CS_range*) is the range (with respect to the transmitting sensor node) within which the other sensor nodes can detect a transmission. It mainly depends on the sensitivity of the receiver (the receive threshold) and the radio propagation properties.

# 4. EXPERIMENTAL RESULTS

In this section we discuss the results of the experiments. In all experiments discussed in the next session, unless explicitly indicated, the default TinyOS and operating parameter values were used. These parameter values are summarized in Table1 and Table 2, respectively.

**Table1. TinyOS default parameter values.**

| | |
|---|---|
| Max message size | 36 bytes |
| Radio data rate | 19.2 kbps |
| Power out | 0 dB/mW |
| Duty Cycle | 100 % |

**Table 2 . Operating parameter values**

| | |
|---|---|
| Motes height from ground | 1 m |
| Distance between motes | 10 m |
| Antenna's disposition | Back to back |

## 4.1 Available Bandwidth

In this section we show that only a fraction of the 19.2 Kbps nominal bandwidth of sensor motes can be used for data transmission. To this end we need to carefully analyze the overhead associated with the transmission of each message. In the TinyOS environment applications invoke the `send()` call to transmit a message to the receiving sensor node. As shown in Figure 2, data included in the `send()` call are passed down to the AM (Active Message) layer where they are enqued for transmission. From this queue data are passed down to the MAC layer, according to a FIFO policy and, then, transmitted over the wireless medium. As soon as the physical data transmission has been completed an acknowledgement signal is propagated up towards the application layer that, eventually, receives a `sendDone()` signal.

Specifically, each message generated by a TinyOS application is encapsulated in a frame by the MAC layer that adds on a 18-byte preamble and 2-byte synchronization information. If we consider a maximum size message, i.e., a 36-byte message, then the corresponding MAC frame will be 56 bytes in size.

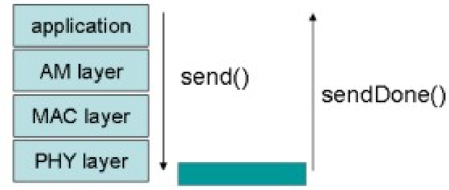


**Figure 2. TinyOS protocol stack.**

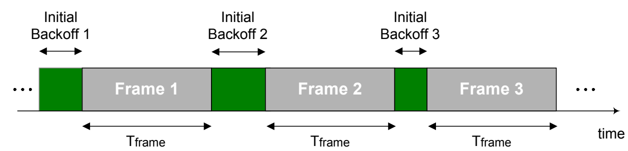


**Figure 3. MAC protocol evolution.**

The MAC protocol described in Section 2 is used for the frame transmission. Figure 3 shows the behavior of the sending sensor node when there is a single couple of communicating sensor nodes (i.e., one sender and one receiver). Since there are only a sender and a receiver all frames are transmitted at the first attempt, i.e., after the initial backoff time. By looking at the above figure, Equation (1) can be derived which provides the theoretical throughput, $T_{th.}$ Specifically, $T_{th}$ is the ratio between the time required to transmit the application data and the overall time the channel is busy due to this transmission.

$$T_{th} = \frac{m}{T_{frame} + \frac{IB_{\min} + IB_{\max}}{2}} \qquad (1)$$

where:

- $m$ is the number of bytes generated by the application;
- $T_{frame}$ is the time required to transmit a MAC data frame at the nominal bandwidth, i.e., 19.2 Kbps. $T_{frame}$ includes the transmission of frame preamble (18 byte) and synchronization bits (2 bytes). For a maximum size frame (56 bytes) $T_{frame}$ is equal to 23.33 ms;
- $\frac{IB_{\min} + IB_{\max}}{2}$ is the average backoff time ( $IB_{\min}$ = 15 ms and $IB_{\max}$ =68.3 ms).

Obviously, the theoretical throughput provided by Equation (1) depends on the message size $m$. For a maximum size message ($m$=36 bytes) the expected throughput is 4.43 Kbps.

We complemented the above theoretical analysis with measurements of the actual throughput achieved at the application level. Specifically, we considered two communicating sensor nodes[1], separated by a distance of 10 m, running an application operating in asymptotic conditions (i.e., the sender sensor node has always messages ready for transmission) with maximum size messages. We measured a throughput of 4.4 Kbps that is very close to the above theoretical throughput (i.e., 4.43 Kbps).

[1] We obtained the similar results with both Mica2 and Mica2dot sensor nodes.

### 4.2 Power Consumption

In this section we characterize the power consumption of mica2/mica2dot motes in different operating modes (i.e., transmitting, receiving, idle, power down). To evaluate the power consumed by a sensor node we measured, by means of a multimeter, the voltage provided by the battery and the current leaked by the sensor. Since the voltage is approximately constant (and equal to 3 V) the power consumed by the sensor is proportional to the leaked current. Therefore, in Figure 4, we compare the power consumption of mica2 and mica2dot sensor nodes in various operating conditions in terms of leaked current. The results in Figure 4 show that mica2 nodes consume more energy than mica2dot nodes in all operating modes. Furthermore, for both types of motes, transmitting is slightly more expensive than receiving.

The power consumption measured when the sensor node is idle and the radio is off (8 mA) is due to the processor activity. Since mica2 and mica2dot use the same processor this value is the same and can be viewed as the basic consumption of the sensor node. The consumption in the power down mode is more than three orders of magnitude lower than that in the idle mode. Therefore, this mode is highly recommended when the sensor node has nothing to do.

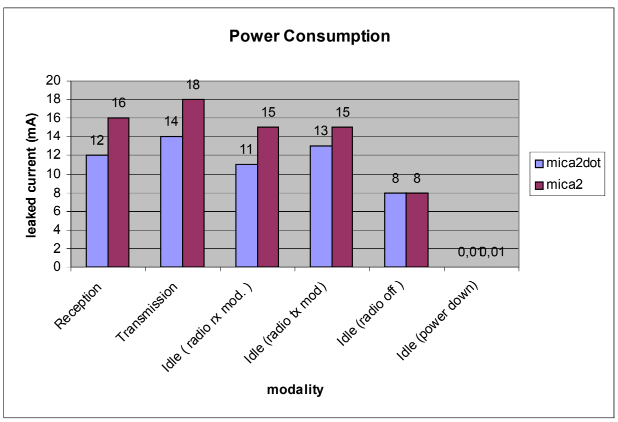


**Figure 4. Power consumption in different operating modes.**

Since mica2 and mica2dot nodes can host various sensor types it is important to measure the energy consumed by different sensors. To this end we considered an application that periodically (every second) senses the physical environment by using different sensors (i.e., magnetometer, photo, etc.). Obviously, to run this application, the CPU, in addition to the specific sensor, needs to be active while the radio is off since there are no data to transmit or receive. The results obtained are summarized in Figure 5. Obviously, to derive the actual power consumed by the specific sensor we need to detract the contribute related to the CPU (i.e., 8 mA). It clearly appears that actual power consumption depends on the specific sensor but it is generally limited.

Finally we measured the power consumption in a real application. We considered a mica2 mote sampling light through a photo sensor every second and transmitting an 8-byte message containing the sampled value to another node. When there are no messages to be sent the radio is switched off and the processor enters the power down mode. The results obtained show that when the sensor is sampling the leaked current is 20mA, while it is 18 mA during transmissions. When the sensor node is in power down mode the current decades to 10 uA.

We found that the average current leaked in every cycle (i.e., 1 sec) is 0.19 mA. This implies that the power consumption is 0.57 mW (assuming a nominal voltage equal to 3V). Using typical lifetime values reported by battery datasheet we can estimate a system lifetime of more than 1 year.

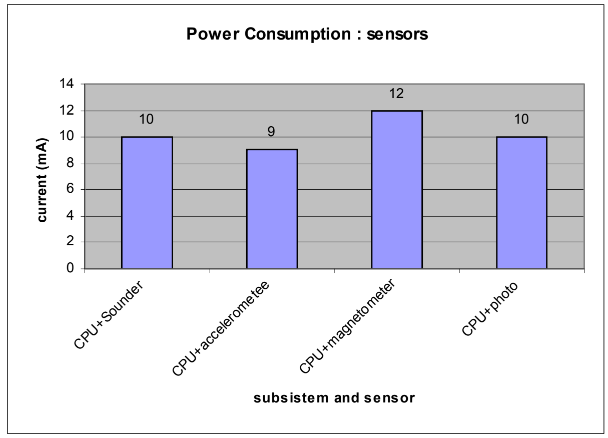


**Figure 5. Power consumption of various sensors.**

### 4.3 Transmission Range

In this section we measure the transmission range of mica2 and mica2dot sensor nodes. The transmission range of a wireless system may be influenced by several factors. The most intuitive one is the transmission power: the more the energy put into a signal, the farther it should travel. However, several additional factors need to be taken into account, including the sensitivity of the receiver[2], the gain and efficiency of the antenna, the data transmission rate, and so on.

We derived the transmission range indirectly by measuring the packet loss rate experienced by two communicating sensor nodes. We considered the default TinyOS settings (see Table 1) and positioned sensor nodes with the antennas in a back to back disposition. Transmitted packets contained a progressive sequence number so that the receiving sensor node could easily recognize a lost packet. By varying the distance between the two communicating sensor nodes we derived the packet loss as a function of the distance. The results obtained for both mica2 and mica2dot sensor nodes are summarized in Figure 6. We can observe that when the distance increases beyond a threshold the percentage of correctly received packets decreases dramatically. This threshold can be assumed as an estimate of the transmission range. By assuming the threshold as the distance at which the percentage of received packets drops below 85%, from Figure 6 it emerges that the transmission range is approximately 55 m for mica2 and 135 m for mica2dot.

[2] Both the transmission strength and the receiver sensitivity are measured in dBm (dB per mW).

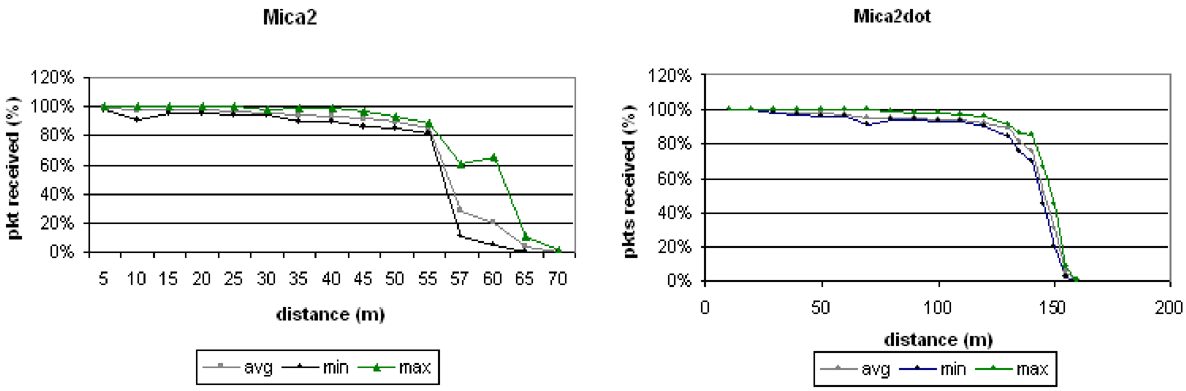


**Figure 6 . Percentage of packets received correctly vs. distance for mica2 (left) and mica2dot (right).**

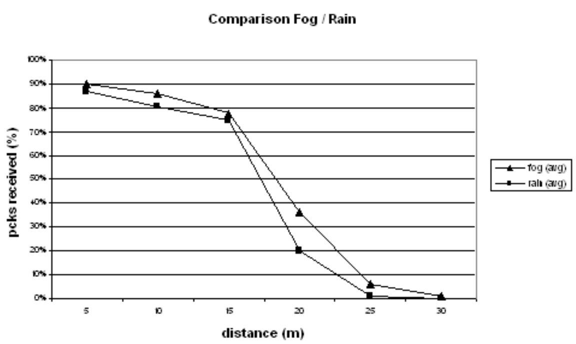


**Figure 7 . Influence of the atmospheric conditions on the transmission range of mica2 sensor nodes.**

By changing the relative antennas' disposition we observed a significant degradation of the communication quality when mica2 were used. In some cases the percentage of the received packets was less than 100% at any distance. This means that mica2 antennae are very directional. On the other hand, we observed that mica2dot nodes are less affected by the relative orientation of the antenna.

It is important to evaluate if and how much the transmission range of a sensor node is influenced by the environmental conditions, such as climatic conditions, atmospheric agents, and so on. By repeating the above experiments in different hours within the same day, we did not observe significant differences in the transmission ranges. This means that motes' performance are not significantly influenced by slight variation in the temperature and/or humidity. On the other hand, we observed a severe performance degradation in the presence of rain or fog. The results obtained in such conditions (for mica2) are reported in Figure 7. We can observe that the transmission range is now in the order of 10 m. This decrease is caused by fog/rain particles that interact with electromagnetic waves and absorb part of their energy causing a signal attenuation.

It is well known that in IEEE 802.11 wireless networks the transmission range strongly depends on the data rate, i.e., it decreases as the data rate increases [2]. We performed a set of experiments to assess whether a similar behavior holds for mote sensor nodes. The results obtained are summarized in Figure 9.

The transmission range of both mica2 and mica2dot sensor nodes is almost independent on the data rate. A possible explanation for this different behavior with respect to IEEE 802.11 stations may be the different range of values for data rates: Kbps (motes) vs. Mbps (IEEE 802.11).

We also investigated the influence of the transmission power. As expected, the transmission range increases with the transmission power. This increase is more than linear both in mica2 and mica2dot. At the maximum transmission power (5dBm) the transmission range is approximately 70 m for mica2 and 230 m for mica2dot sensor nodes.

While performing the experiments described so far, we also observed a dependence of the transmission range from the sensor node's height from the ground. Specifically, in some cases we observed that the devices were not able to communicate when located on the stools and they started to exchange packets by lifting them up. By carefully investigating this effect we obtained the results summarized in Figure 8. The distance between the sensor nodes is 10 m. Only when the distance from the ground is 1m or beyond the percentage of packet losses can be considered as negligible.

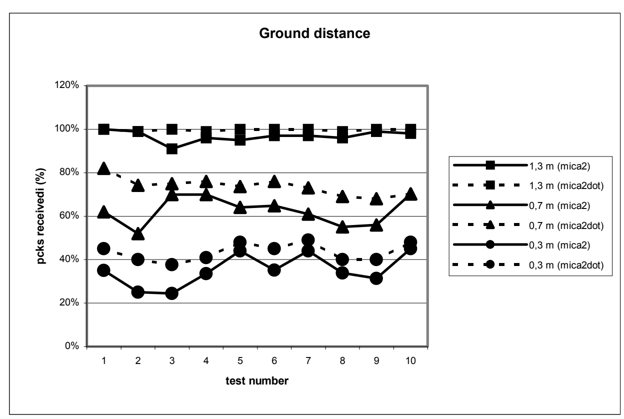


**Figure 8. Influence of the sensor node's height from the ground.**

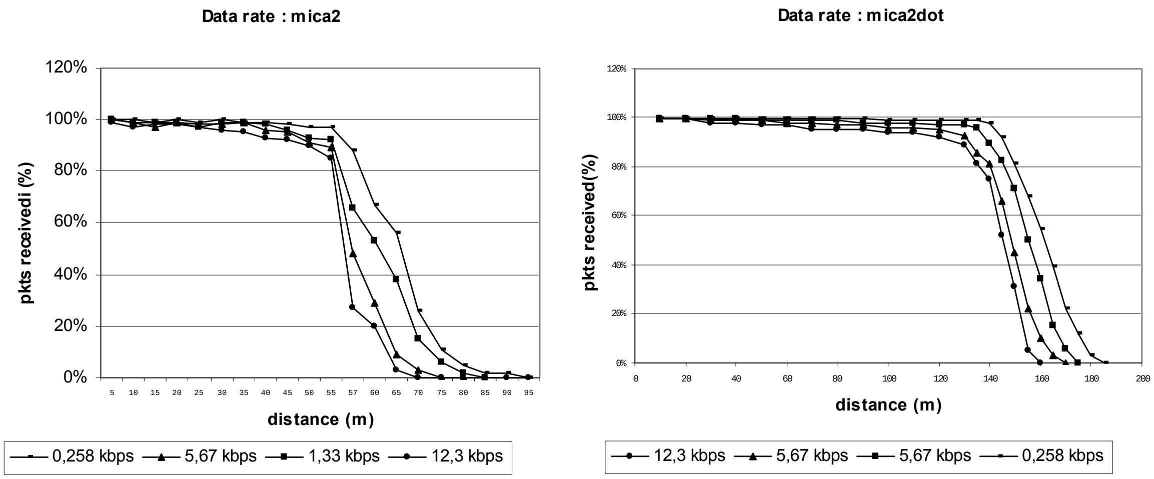


**Figure 9. Influence of the data rate on the transmission range of mica2 (left) and mica2dot sensor nodes (right).**

A similar behavior is also exhibited by IEEE 802.11 stations [2]. [9] provides a theoretical framework to explain the height impact on channel quality. Specifically, the channel power loss depends on the contact between the Fresnel zone and the ground. The Fresnel zone for a radio beam is an elliptical area with foci located in the sender and the receiver. Objects in the Fresnel zone cause diffraction and, hence, reduce the signal energy. Specifically, most of the radio-wave energy is within the First Fresnel Zone, i.e., the inner 60% of the Fresnel zone. Hence, if this inner part contacts the ground (or other objects) the energy loss is significant. Figure 10 shows the Fresnel zone (and its inner 60%) for a sender-receiver couple at a distance D. In the figure, R1 denotes the height of the First Fresnel Zone. As shown in [9], R1 is highly dependent on the distance between sensor nodes.

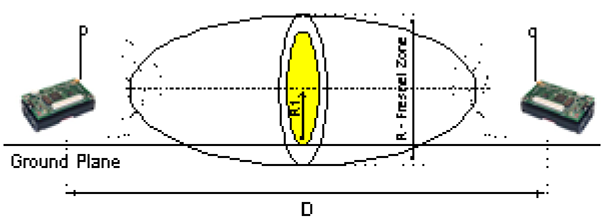


**Figure 10. The Fresnel zone.**

## 4.4 Physical Carrier Sensing Range

The characteristics of the wireless medium make wireless networks fundamentally different from wired networks. Specifically:

- the wireless medium has neither absolute nor readily observable boundaries outside of which nodes are known to be unable to receive network frames;
- the channel is unprotected from outside signals;
- the wireless medium is significantly less reliable than wired media;
- the channel has time varying and asymmetric propagation properties;

In this section we investigate, by a set of experimental measurements, the relationship between the transmission range (TX_Range) and the carrier sensing range (CS_Range). To this end we designed some experiments to estimate the carrier sensing range of a sensor node. A direct measure of this quantity seems difficult to achieve because with motes it is not possible to have information about the channel carrier sensing. Therefore, we defined an indirect way to perform these measurements. We utilized the scenario shown in Figure 11 with fixed distance between each couple of communicating sensor nodes (d(A,B)=d(C,D)=10 m), and variable distance between the two couples (i.e., d(B,C) is variable).

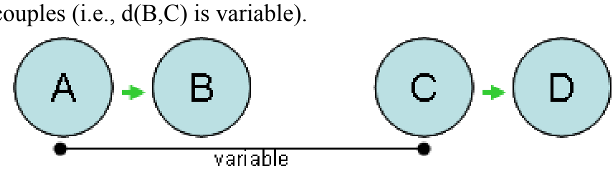


**Figure 11. Reference network scenario.**

The idea is to increase d(A,C) until no correlation is measured between the couples of sensor nodes. To quantify the correlation degree we measured the throughput achieved by each couple of (mica2dot) sensor nodes when both couples are active and we compared it with the throughput achieved by each couple in isolation. This throughput was already measured in Section 4.1 (4.4 Kbps). Obviously, no correlation exists when the throughput achieved by each couple of sensor nodes is equal to the throughput achieved by the same couple in isolation.

Figure 12 shows the throughput achieved by each couple, as well as the aggregate throughput, as a function of the increasing distance d(A,C). For comparison we also reported the throughput in isolation ($t_{IS}$). We can observe two steps in the behavior of the aggregate throughput: one after 275 m and the other after a distance of 450 m.

This behavior can be explained as follows. Taken a couple as reference, the presence of the other couple may have two possible effects on the performance of the reference couple:

- if the two couples are within the same carrier sensing range they share the same physical channel. Therefore, the throughput achieved by each couple is minor than that measured in isolation (i.e., 4.4 Kbps). The aggregate throughput tends to increase slightly with the distance d(A,C) due to the minor interferences between the couples.
- if they are outside the carrier sensing range the radiated energy from one couple may still affect the quality of the channel observed by the other couple. As the radiated energy may travel over unlimited distances, this effect completely disappears only for very large distances (e.g., d(A,C)=450 m). The individual throughput achieved by each couple speeds up and tends to the throughput in isolation.

Hence we can assume that the first step coincides with the end of the carrier sensing range, while the second one occurs when the interference between the two couples becomes almost negligible.

We also performed experiment with different data rates. We found that the carrier sensing range is almost the same for different transmission rates. Indeed, the carrier sensing mainly depends only on two parameters: the sensor node's transmitting power and the distance between transmitting nodes. The rate at which data are transmitted have no significant effect on these parameters.

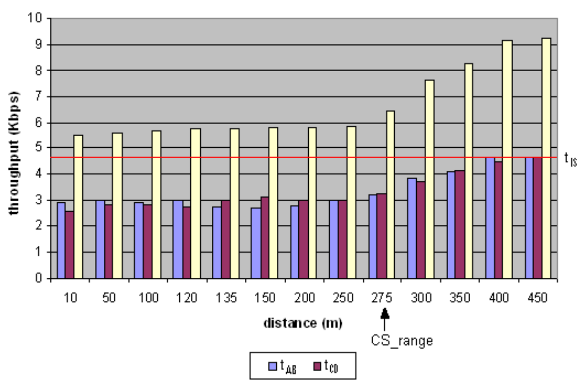


**Figure 12. Throughputs vs. distance.**

# 5. CHANNEL MODEL FOR MICA2 AND MICA2DOT MOTES

The results presented in this paper indicate that to correctly understand the behavior of mote sensor nodes, several different ranges must be considered.

Specifically, as shown in Figure 13, given a transmitting sensor node *S*, sensor nodes around *S* will be affected by S's transmissions in a different way depending on their distance from *S*. Specifically, sensor nodes around S can be partitioned into three classes depending on their distance, *d*, from *S*:

- sensor nodes at a distance d<TX_Range are able to correctly receive data from *S*;
- sensor nodes at a distance d, where TX_Range<d<CS_Range, are not able to receive data correctly from *S*. However, as they are in the S carrier sensing range, when S is transmitting they observe the channel busy and thus they defer their transmissions;
- sensor nodes at a distance d>CS_Range do not measure any significant energy on the channel when *S* is transmitting, therefore the can start transmitting contemporarily to *S*; however, the quality of the channel they observe may be affected by the energy radiated by S.

The above model is very similar to the channel model of IEEE 802.11 stations [2]. However, with IEEE 802.11 the transmission range highly depends on the data rate of the transmitting stations. On the other hand, our experimental analysis has shown that the transmission range of mica2/mica2dot sensor not do not depend on the available data rates (see Section 4.3).

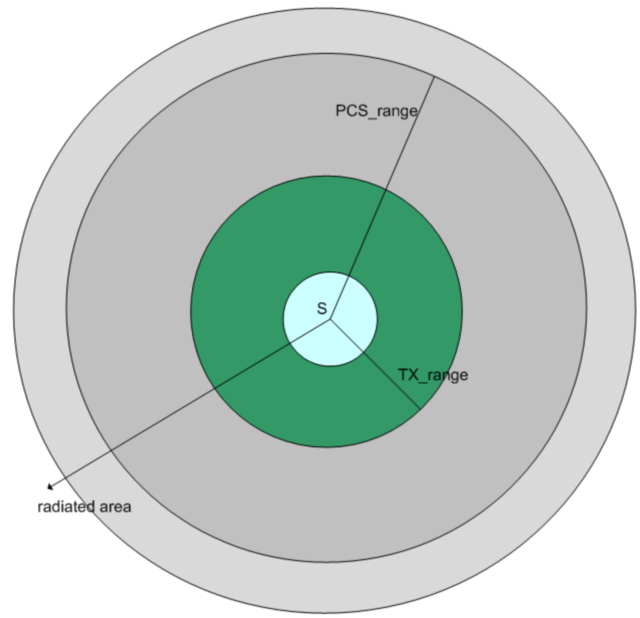


**Figure 13. Channel model for mica2 and mica2dot motes.**

# 6. SUMMARY AND CONCLUSIONS

In this paper we have presented the results of an extensive measurement analysis on mica2 and mica2dot Berkeley motes. This analysis was aimed at investigating the main elements that characterize the sensor network performance, e.g., impact of weather conditions on the transmission range, energy consumption in different operating conditions, etc. To this end the experiments were done in an outdoor environment under various atmospheric conditions. The main results of this experimental analysis are summarized in Table 3.

Although the analysis is strictly related to a specific technology (i.e., Berkeley motes) we nevertheless think that the results obtained still provides general useful information. We found that the transmission range of mica2/mica2dot sensor nodes significantly decreases in the presence of fog or rain. In addition, we found that there is a minimum distance from the ground at which sensor nodes should be set. These aspects need to be taken into account for a correct deployment of sensor nodes.

Based on our experimental results, we also derived a channel model for the CSMA/CA MAC protocol used in motes. This model is very similar to the IEEE 802.11 channel model. Since many simulation studies on sensor networks assume the IEEE 802.11 CSMA/CA protocol to characterize the physical and data link layers, our findings prove that this choice can be considered as acceptable, at least as far as the channel model is concerned.

## Acknowledgements

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**Table 3. Summary of the main experimental results.**

| | mica2 | mica2dot |
|---|---|---|
| | | |
| **Available throughput** | 4.6 Kbps | 4.6 Kbps |
| | | |
| **Power Consumption** | | |
| Reception | 16mA | 12mA |
| Transmission | 18mA | 14mA |
| Computation (processor only) | 8 mA | 8 mA |
| Power down mode | 10 uA | 10 uA |
| | | |
| **Transmission range** | | |
| with normal weather conditions | 55 m | 135 m |
| with fog/rain | 10 m | |
| with maximum tx power (normal weather conditions) | 70 m | 230 m |
| Minimum ground distance | 1 m | 1 m |
| Minimum horizontal distance | 50 cm | 50 cm |
| | | |
| **Carrier sensing range** | | 275 m |

# 7. REFERENCES


[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, "Wireless Sensor Networks: a Survey", Computer Networks, Vol. 38 (2002), pp 393-422

[2] G. Anastasi, E. Borgia, M. Conti, E. Gregori, **"**Wi-Fi in Ad Hoc Mode: A Measurement Study", *Proceedings of the IEEE International Conference on Pervasive Computing and Communications (PerCom 2004)*, Orlando (Florida), March 14-17, 2004.

[3] Berkeley TinyOS project http://webs.cs.berkeley.edu/tos/

[4] Crossbow , "User Manual: MPR - Mote Processor Radio Board, MIB - Mote Interface, Programming Board User's Manual" , 2003

[5] Crossbow , "MTSMDA sensor and data acquisition boards user's manual MTS101CA , MTS300CA , MTS310CA , MDA300CA , MDA500CA", 2003

[6] Crossbow, "TinyOS Getting Started Guide" , 2003

[7] Crossbow , "TinyOS Tutorial" , 2003

[8] J. Elson and D. Estrin, "Time Synchronization for Wireless Sensor Networks", *Proceedings of the Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing*, April 2001, San Francisco, CA, USA, pp. 1965--1970.

[9] D. B. Green, M. S. Obaidat, "An Accurate Line of Sight Propagation Performance Model for Ad-Hoc 802.11 Wireless LAN (WLAN) Devices", *Proceedings of IEEE ICC 2002*, New York, April 2002.

[10] IEEE standard 802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, August 1999.

[11] C. Intanagonwiwat, R. Govindan, D. Estrin , "Directed diffusion: a scalable and robust communication paradigm for sensor networks", *Proceedings of the International Conference on Mobile Computing and Networking (Mobicom 2000)*, August 6 - 11, 2000, Boston (MA)

[12] S. Madden, R. Szewczyk, M. Franklin, D. Culler, "Supporting Aggregate Queries Over Ad-Hoc Wireless Sensor Networks", *Proc. of the Workshop on Mobile Computing and Systems Applications*, 2002.

[13] The Network Simulator - ns-2, http://www.isi.edu/nsnam/ns/index.html.

[14] V. Raghunathan, C.Schurgers, S. Park , M. Srivastava, "Energy-aware Wireless Microsensor Networks", *IEEE Signal Processing Magazine*, March 2002.

[15] Y. Sankarasubramaniam, O. Akan, I. Akyildiz, "ESRT: Event-to-Sink Reliable Transport in Wireless Sensor Networks" *Proc. of the ACM MobiHoc Conference*, Annapolis, Maryland, June 2003.

[16] A. Wadaa, S. Olariu, L. Wilson, M. Eltoweissy, and K. Jones, Training a Sensor Network, *ACM/Kluwer Mobile Networks and Applications (MONET)*, June 2004, to appear.

[17] C. Wan, A. Campbell, L. Krishnamurthy, "PSFQ: A Reliable Transport Protocol For Wireless Sensor Networks," *First Workshop on Sensor Networks and Applications (WSNA)*, September 2002, Atlanta, GA.

[18] C. Wan, S. B. Eisenman, A.T. Campbell, "CODA: Congestion Detection and Avoidance in Sensor Networks," *ACM SenSys* , 2003.

[19] A. Woo, D. Culler, **"**A transmission control scheme for media access in sensor networks", Proceedings of the International conference on Mobile Computing and Networking (Mobicom 2001), Rome (Italy)

[20] Y. Xu, S. Bien, Y. Mori, J. Heidemann, D. Estrin , "Topology Control Protocols to Conserve Energy in Wireless Ad Hoc Networks" , *CENS* Technical Report #6 , January 11 2003