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A MAC Protocol for Wireless Sensor Networks with Multiple Selectable, Fixed-Orientation Antennas

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Abstract

One of the open issues in sensor network research is the efficient operation while having energy constraint sensor nodes and dense networks. One potential approach to improve the energy usage is the application of directed data transmission / reception in order to improve the energy usage and decreases the probability of transmission conflicts. To do so, appropriate medium access control protocols are required that decide which antennas to use for sending and receiving, in a distributed fashion. We extend existing protocols for selectable antennas and study their performance. As a main result of this performance evaluation, we derive recommendations on how many antennas per node should be used and how high the performance benefits for an increasing number of antennas is. We show considerable improvements in number of retries (up to 87 %) and per-hop delay (up to 24 %), depending on load characteristics and network density.

Dichte Netze von Sensoren mit begrenzter Energiekapazität ist eine der offenen Fragen im Forschungsbereich Sensornetze. Eine möglicher Ansatz zur Verbesserung der Energieausnutzung und zur Reduzierung der Kollisionswahrscheinlichkeit in solchen Netzen ist die Verwendung von gerichteten Antennen zum Empfang und zum Versenden von Daten.

Um dies zu erreichen sind geeignete Medienzugriffsprotokolle erforderlich, die in verteilter Weise entscheiden, welche Antenne zu welchem Zeitpunkt zum Senden und Empfangen benutzt werden soll. Wir erweitern in dieser Arbeit existierende Protokolle für solche wählbaren Antennen und untersuchen deren Leistungsfähigkeit. Als wesentliches Resultat dieser Leistungsbewertung geben wir Empfehlungen zur Anzahl Antennen pro Knoten und charakterisieren die möglichen

Leistungsgewinne durch eine steigende Anzahl von Antennen. Wir zeigen deutliche Gewinne bei der Anzahl der Übertragungswiederholungen (bis zu 87 %) und Verzögerung (bis zu 24 %) in Abhängigkeit der Lastcharakteristik und der Dichte des Netzes.

1 Introduction

Wireless sensor networks (WSNs) will enable new applications of embedded, pervasive observation and control that is, with current technology, not feasible. Much of the required advances of technology are in the areas of actually building sensor nodes, to make them small, self-contained, cheap, and highly energy efficient – this special issue has described a number of research efforts concerning hardware. But equally important to hardware advances are tailor-made communication protocols that support the very specific communication patterns of a wireless sensor network and achieves the required energy efficiency of the communication – any progress in hardware can easily be squandered by improperly designed communication protocols.

The design of energy efficient, self-organizing communication protocols has already been considered in the context of so-called mobile ad hoc networks (MANETs), and a number of the research can be reused. But wireless sensor networks will exhibit quite distinct usage patterns. While MANETs are primarily intended for human-to-human communication, the typical use cases for WSNs are more likely to be *event detection*, *monitoring*, *function approximation*, and *tracking*. In an event detection scenario, a WSN is used to decide whether a given event has happened, e.g., an intruder has entered an area under surveillance. In monitoring applications, periodic measurements shall be reported. Function approximation applications are a more sophisticated version in that the shape of a function, e.g., a temperature distribution over a given area, shall be computed as efficiently as possible. Lastly, tracking applications required the WSN to be constantly able to provide the location of a given event, e.g., again an intruder.

In all these cases, the results of these measurements might be required at a central point, or they might have to be distributed to all or many nodes in a network so that requests can be made at any point in the network (e.g., in tracking applications). Moreover, the temporal behavior of these applications is quite different: While periodic monitoring applications can exhibit traffic with a low average bandwidth that is well spread in time, event detection or tracking applications will typically have very bursty traffic where the long-term average bandwidth is also quite small, but once an event is detected, a lot of sensors will start to report measurements and hence a highly correlated, short term burst of traffic will ensue. Hence, the traffic patterns are very different form usual mobile ad hoc networks and consequently, new communication protocols are required to achieve maximum efficiency.

Such new protocols must also make best possible use of the underlying hardware and adapt to its constraints. As a case in point, consider the AVM nodes' intended feature of multiple antennas, which can be switched so that sending or receiving (predominantly) takes place only in a given direction? While the concept of such "smart antennas" is well known and protocols for them have been developed, these protocols usually assume more functionality than is available in a sensor node (e.g., actual beam forming), nor are they adapted to the peculiar traffic patterns of wireless sensor networks.

Such an adaptation should result in a number of benefits: the concentration of the emitted power in a single direction would allow longer distances to overcome for a given power consumption, but also the contention for the medium is reduced as multiple transmissions could take place in parallel which would have to be serialized when using omnidirectional transmissions. Hence, a properly modified medium access control (MAC) protocols – the functionality which decides when a given node is allowed to send or receive data – could to leverage the potential benefits of such switchable antennas by reducing the delay of a transmission, the number of packet collisions and resulting retransmissions, and the goodput that is achievable when highly correlated traffic patterns occur.

It is such a modification for a MAC protocol that we investigate in this paper. Evidently, this is not the only research problem concerning communication protocols in WSNs – an overview can be found in, e.g., reference [4]. Nor is it the only problem considered in the AVM project; in addition, network-layer and service discovery questions are considered as well.

The remainder of this paper is organized as follows. We shall first, in Section 2, discuss related approaches for MAC protocols using selectable antennas. Section 3 describes our extensions to existing protocols. Section 4 describes the simulation setup and basic assumptions, Section 4.2 the concrete scenarios that we used for a performance evaluation of our protocol. Finally, Section 5 presents the evaluation results and Section 6 contains conclusions and future work.

2 Related work

In a wireless network, the main purpose of a MAC protocol is to ensure that no transmission is interfered with at the receiver by a concurrent second transmission from some other node, resulting in packet loss. While this is equivalent to the MAC problem in wired networks, the main difference is that in a wireless network, the sender has no means of knowing about the interference level at the receiver – in an Ethernet, for example, it is usually completely acceptable to equate interference levels at the receiver with that at the sender. Hence, explicit information exchange between sender and receiver is necessary.

One popularly used mechanism for such information exchange is the "Request to Send/Clear to Send" (RTS/CTS) mechanism, popularized by the IEEE 802.11 protocols. The idea is that the sender requests the receiver for permission to send a packet. As both messages contain the time necessary for the packet exchange (including an acknowlegdement), all nodes in the vicinity of either sender or receiver know for how long the have to abstain from transmission. Thus, the protocol can help to combat (but cannot completely avoid) the "hidden terminal" problem [5]. While this RTS/CTS approach has its shortcomings [3, 8, 9, 12–14], it works reasonably well to serve as a starting point.

It is important to point out that the plain IEEE 802.11-type protocols are not particularly suited to WSNs. They can, however, be extended to work in these environments as well, e.g., by introducing synchronized sleep cycles into the protocol as demonstrated by the S-MAC protocol [15]. These extensions are, however, orthogonal to the use of selectable antennas and are therefore not further discussed here. [1]

Introducing selectable antennas into a WSN holds great promises as they can greatly reduce the level of interference and increase concurrency in the system. The question is, however, how to decide in which direction to listen or to send. This is challenging since turning off sending or receiving in some direction also limits the information exchange with other neighbors that is necessary to prevent transmissions that will interfere with an on-going transmission. A protocol hence has to balance between the reduced interference of directed transmissions, but must still ensure that enough information is exchanged between nodes. Several proposals to do so exist.

Nasipuri et al. [11] used directional antennas in their MAC protocol. They perform an omnidirectional RTS/CTS handshake and a directional data transmission. The handshake was only used to inform the neighborhood to keep silent during the DATA transmission phase and to discover the direction the beam has to focus on. The observation of spatial reuse possible with directional antennas was made by Ko et al. [6], but they reduced the RTS/CTS handshake to one particular antenna, neglecting the effect of hidden terminals due to unheard RTS/CTS. Choudhury et al. discovered these and additional problems using directional antennas [1]. But they assumed that directional antennas have a higher gain (can overcome a longer distance) than omnidirectional antennas. They created a fairly complex channel reservation mechanism, neglecting the option of power control at transmission time to adapt the achievable antenna gain. We assume a different antenna pattern in this paper. We have multiple, independent antennas pointing to all possible directions. These antennas can be linked together to form an omnidirectional antenna, thus the reception gain in any direction does not depend on the number of antennas used. In reference [7], Kobayashi and Nakagawa also used the RTS/CTS on all available antennas like in our paper to inform the neighborhood of ongoing transmission, but they did not consider the effect of side lobes when using directional antennas. Additionally, they assumed that every antenna has its own receiver

[1] An explicit integration of such synchronized sleep cycles with selectable antennas is actually an issue for further work.

circuit to decode the data received on this particular antenna, which can be considered as an independent node, especially when considering production costs and hardware size.

3 An extended MAC protocol for selectable antennas

3.1 Hardware assumptions

Before we can describe the protocol, we have to clarify the assumed hardware structure of a sensor node. We assume that every node has a fixed number n of antennas. In a "vertical" orientation, all antennas transmit/receive to/from over all full 180 degree arc; in the "horizontal" orientation, each antenna covers a $360/n$ degree arc. To account for imperfections, antennas also are assumed to have slide lobes; numeric details are given in Section 4. This configuration is outlined in Figure 1. We shall further assume that nodes are always oriented with the main axis pointing upright so that the n sectors extend horizontally, but nodes can be rotated at arbitrary angles around this axis.

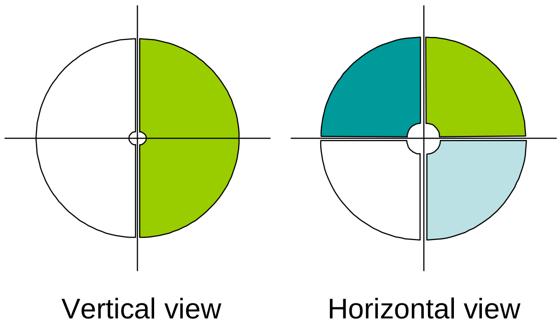

Figure 1: Antenna configuration illustrated for four antennas

An node has the option to use all antennas simultaneously, resulting in omnidirectional transmission/reception. Alternatively, a node can, while sending or receiving, decide to turn off some of the antennas. The signal is then only transmitted over the active antennas in their respective sectors (and along their sidelobes); during reception, only signals and interference from the active antennas (again taking into account their sidelobes) is accounted for.

This behavior only requires a single transceiver per node. Alternatively, it might be worthwhile to contemplate using multiple receivers per node so that information from the hitherto silenced antennas can be fed to these additional receivers, e.g., to try to observe other reservation messages going on to avoid later collisions. But as this would raise both hardware and software complexity considerably, we leave this approach for further study.

Moreover, we assume that antennas cannot be flexibly combined in the sense of "smart antennas" to form a beam into any arbitrary sector. Once a node has been placed, the physical configuration of its antennas determines which geographic sectors can be separately addresses – hence, we speak of "selectable" antennas and can use the terms "antennas" and "sector" interchangeably.

These hardware assumptions result in a specific behavior during reception and transmission, described next.

3.2 Receiving sequence

After a sensor node is back to an active state – for example, due to the wake up signal issued by a sensor node which needs its neighbors to forward its data over multiple hops – the nodes listens omnidirectionally to the channel with all of its antennas. Then, when a signal on one of its antennas is strong enough to mark the beginning of a packet reception, the node determines the antenna which provides the highest signal level and shuts down the other antennas. As the reception pattern of any antenna is not perfect, this shutdown of antennas does not void the influence of the silenced antennas, it only reduces the antenna gain for the inactive antennas during packet reception.

At the end of the reception the packet is marked with the direction it came from, i.e., which antenna had the strongest signal for receiving the packet. Then the node returns to omnidirectional listening mode.

3.3 Transmission sequence

Before a sensor node is going to send any data, it has to know which antennas are involved. As this information is a neighborhood information and in our case stored in the MAC layer, the MAC layer has to mark every outgoing packet with the antennas this packet has to be radiated on. The number of antennas determines the output power provided by the final amplifier. The more antennas are involved, the more output power is necessary to have an antenna radiate the same amount of power regardless of the number of antennas involved.

3.4 MAC Protocol description

Based on these prescribed behaviors for reception and transmission, the actual protocol works as follows: Before the actual data packet is transmitted the sender issues a request to send (RTS) message. When the target node overhears this RTS packet it responds with a clear to send (CTS) message – informing the sender that it is awake and ready to receive the actual data.

To organize, in a distributed manner (between all the sensor nodes), the future use of the channel (on a packet-per-packet basis) the information of transfer times for a particular data packet should be spread to neighboring nodes. This transfer time can derived by the receiver (based on explicit information from the protocol messages or implicitly when using fixed-size data packets) and used to silence neighboring nodes. The receiver stores this time in a so-called "network allocation vector" (NAV), which is used by the MAC protocol to delay a new tranmission that otherwise would disturb an already ongoing transmission. As we use multiple antennas, we have to use a NAV for every antenna — the directional network allocation vector (DNAV) – otherwise all antennas would be needlessly silenced.

In order to have valid and helpful information stored in the DNAV, both RTS or CTS packets should be widely spread. This is achieved by using all free antennas (not blocked by the NAV of this particular antenna) when transmitting RTS or CTS. The actual data and the ACK packets, on the other hand, are only sent on the antenna which has had the strongest signal when receiving the RTS or CTS, respectively. In addition, nodes not part of the actual transmission modify their behavior accordingly after reception of either RTS or CTS: instead of abstaining from transmission entirely for the packet during, they only turn off the sector from which the control had been received by entering that information in the related DNAV; these nodes are free to pursue communication with other nodes using any still free antenna. The backoff procedure is identical to IEEE 802.11.

This protocol is illustrated in Figure 2: Node 1 initiates a transmission to node 2; node 3 is a non-involved node nearby. After the RTS/CTS exchange (left half), the actual data exchange is undertaken using the sender's antenna 2 and the receiver's antenna 0; antenna 0 of node 3 is blocked while this communication is on-going as node 3 had received the CTS most strongly via this antenna.

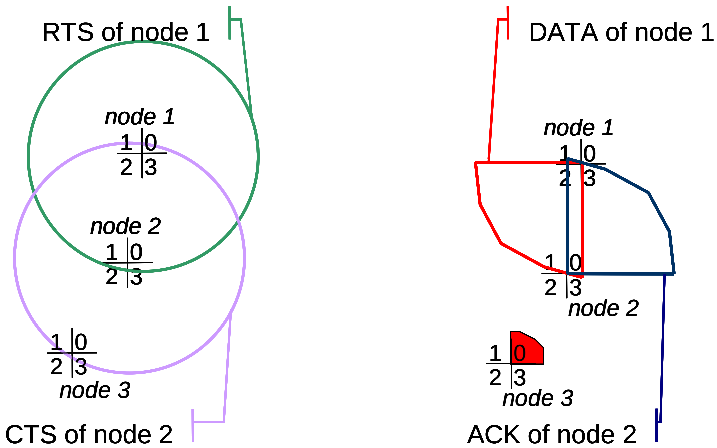

Figure 2: Illustration of directional RTS/CTS MAC protocol

This modification of RTS/CTS tries to overcome its weaknesses by using multiple antennas.

4 Simulation setup

In the following we will give an overview on parameters we chose, factors we changed to see their impact on our MAC protocol and a description of the metrics used to evaluate the results.

4.1 Fixed parameters

We chose to parameterize our performance evaluation using the characteristics of the 2.4 GHz ISM band. The radiated power was chosen to allow communication with other nodes which are up to 250 m away; the received power at this maximal distance has to be larger than receiver sensitivity and has to result in a minimum SNR of 4 dB in absence of any interference. These values are comparable to other research using this ISM band. Interference caused by any sensor node was only considered for distances up to 550 m. The raw data rate was 2 Mbps and every sensor node has a packet queue of 50 packets.

The antenna side lobes have an impact on sensitivity with respect to the other directions/sectors of the node, i.e., sectors which are closer to the radiating antenna are more sensitive (while receiving) or also radiating (while transmitting). For our simulation we chose a ratio of 20 dB for power suppression between the main sector (transmitting antenna) and its adjacent sector (adjacent antenna), 30 dB for the sector following the adjacent antenna, and 40 dB for all remaining antennas for both transmission and reception.

As the payload necessary for sensor readings is quite small [10], we fixed the data packet size to 64 bytes. As this fixed size reduces the amount of information necessary to be spread to the neighbors, we dismissed it from the RTS, CTS and ACK packets, but used the IEEE 802.11 standard for the remaining parameters like backoff time and inter frame times.

In order to find the shortest path in this wireless networks, no wireless routing protocol was directly applied. Instead, Dijkstra's algorithm [2] was used (having global information) to determine the shortest path for packet transmission. This allowed us to look at MAC effects in isolation without tainting the results with ad hoc routing protocol imponderables.

4.2 Variable factors

As the introduction has discussed, there is no single load pattern that would encompass all sensor network applications. Therefore, two different scenarios are used to capture a wider range of possibilities: a) all sensor nodes send their readings to a data sink that resides in the middle of the network; b) all sensor nodes randomly select another sensor node as their target and transmit all sensor readings to the target sensor node for a duration of 30 seconds, afterwards, a node chooses a new destination.

For both these scenarios, we varied the offered load by changing the packet creation rate in the sensors. Also, and most importantly, we used different numbers of antennas, trying to understand the benefits of an increasing number of antennas.

4.3 Observed metrics

As figures of merit, we are particularly interested in the number of retries per hop and packet – how often does a packet have to be retransmitted? This metric is intimately tied to the energy efficiency of a MAC protocol. Also, the delay per hop is an interesting metric as it allows to understand the responsiveness of a protocol.

For every following graph, results from 20 simulations with different layouts of nodes (randomly chosen with uniform distribution) were averaged. Every layout had 80 nodes and the simulation run for half an hour simulated time. The packet creation time was between 0.4 packet per second and 2 packets per second. All figures are displayed with a 95 % confidence interval.

5 Results

Considering first scenario a), we are interested how varying the offered load influences our figures of merit. Figure 3 shows the average number of retries over the offered load of sensor readings. The resulting average number of retries depends not only on the offered load and is thus a result of collisions or bit errors, it also depends on the number of antennas. Doubling the amount of antennas cuts the performed retries nearly in half, i.e., using 2 instead of 1 antenna reduces the average number of retries by 47 % to 49 % over all simulated loads. Additionally, increasing the number of antennas to 4 and 8 reduces the retries by 68 % to 71 % and 86 % to 87 %, respectively.

Another interesting behavior is the per hop delay in such multi hop sensor network, as depicted in Figure 4. It is interesting to note that the per hop delay does not strongly depend on the offered load (as this load is in sensor networks not very close to its maximum), even for the case of 1 antenna where the wide confidence indicates only a large variation in per hop delays between the various setups, but no real differences in per hop delay. The difference between 1 antenna and 2, 4, and 8 antennas is only a result of the back off scheme used. In the 1 antenna case the sensor node is more often in a state of back off, especially when located near the data sink in the middle of the area.

Figure 5 shows the number of average retries necessary in the second scenario (the sensor-to-sensor communication). One can see that we have a similar decrease in number of retries as in scenario a) when 2 antennas instead of 1 antenna are used – 44 % less retries are necessary at an offered load of 100 Kbps. It also extends to 71 % with

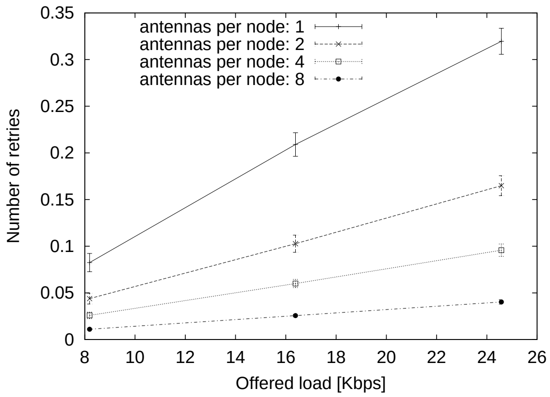

Figure 3: Average number of retries over offered load, number of antennas = 1, . . . , 8

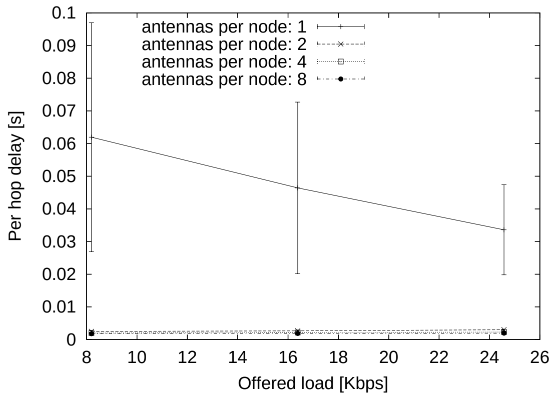

Figure 4: Average per hop delay over offered load, number of antennas = 1, . . . , 8

4 antennas and 82 % with 8 antennas. But it is interesting to note that with increasing load the gain using additional antennas diminishes to only 23 % gain with 2 antennas, 57 % gain with 4 antennas and 77 % with 8 antennas. This is due to the saturation of the network as can be seen in Figure 6.

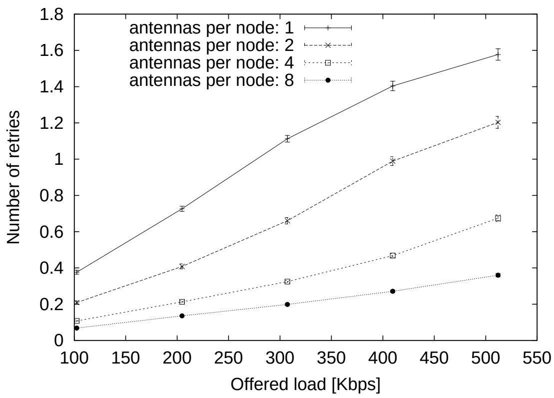

Figure 5: Average number of retries over offered load, number of antennas = 1, . . . , 8

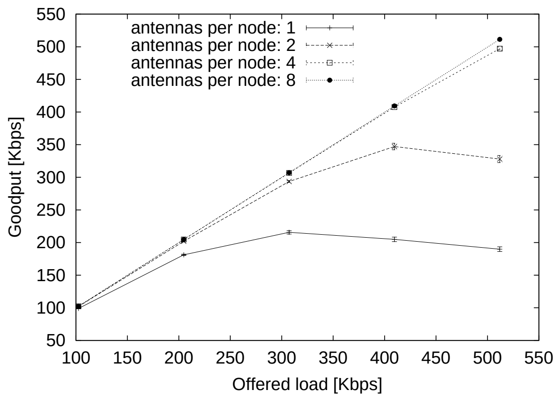

Figure 6: Goodput over offered load, number of antennas = 1, . . . , 8

Figure 6 shows the goodput (number of correctly received packets) over the offered load. When using only 1 antenna the network approaches its maximum goodput of 215 Kbps at an offered load of 307 Kbps. Increasing the load does only result in more collisions and thus reduces the total goodput. But, when using 2 antennas per node the maximum goodput of 347 Kbps is achieved at an offered load of 410 Kbps, which is an improvement of maximum goodput by 70 %. From the curve for 4 and 8 antennas it is quite obvious that these setups are not even near to their maximum goodput as both can provide more than 97 % of the offered load at 512 Kpbs.

Figure 7 shows the per hop delay over the network density.

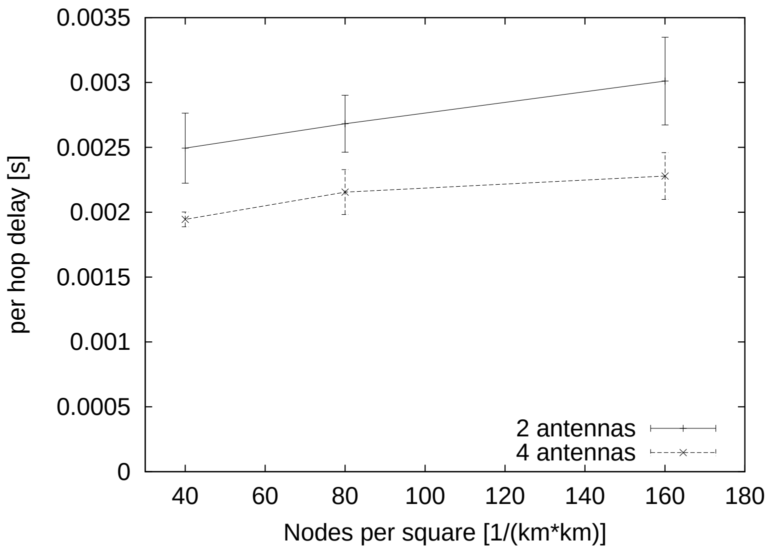

Figure 7: Per hop delay over density, number of antennas = 2, . . . , 4

As we used 80 nodes for all different scenarios, we varied the size of the network to investigate density effects. The maximum size ($1414\ m \times 1414\ m$) was chosen to have networks which are still connected, i.e., via multi-hopping every node can communicate with all other nodes. The size of the network was lowered in two steps, with every step the number of nodes per square was doubled.

Figure 7 shows that with increasing density the *per-hop* delay increases, e.g., with 40 nodes per square the delay is less than 2.5 ms with 2 antennas and less then 2 ms with 4 antennas. When the density is increased to 160 nodes per square, the per-hop delay grows to 3.0 ms and 2.2 ms, respectively. In order to maintain a certain per-hop delay, e.g., 2.5 ms, it is necessary to use 4 antennas per node in denser networks.

6 Conclusions & future work

As our results show, using multiple antennas lowers not only the average retries necessary to transfer a packet successfully from one sensor node to another (which was our main metric), it also confirms the intuition that using more antennas is helpful to reduce the retries necessary in dense networks. As these observations are made with an offered load not exceeding the network capacity, another interesting outcome is the behavior under higher load. With an offered load approaching the network capacity, the decrease in retries using multiple antennas does not continue with the same ratio. Instead, the ratio at higher load decreases as the different networks (different number of antennas) reach their maximum goodput. As a practical recommendation, nodes should be equipped with at least two antennas; with four antennas, almost all of the potential benefits can be obtained; the additional advantage of going to eight antennas is quite small in the scenarios considered here.

As we considered wake up of nodes only in a broadcast sense, all sensor nodes in the vicinity of the calling node become awake, another interesting topic is dedicated wake up — the calling node can address one dedicated neighbor and all the other nodes are not required to become awake. Additionally, as we only considered two types of traffic, it might be interesting to develop special MAC protocols, based on certain properties of other types of traffic, e.g., information waves coming and going multihop to a sink.

Our investigation was based on the assumption that a sensor node has multiple antennas (which can be combined) but has only one receiver circuit. Hence, it can only decode one stream of information at a time. As we already could show a significant gain using multiple antennas, it is interesting to see whether a dedicated receiver circuit for each antenna would further improve the performance of such sensor networks. Then, both cost and energy overhead of such a more complicated solution should be compared to the simple, single-receiver approach. At the end, we will be able to give recommendations on the hardware structure for the AVM node from a medium access efficiency point of view.

References

[1] Romit Roy Choudhury, Xue Yang, Nitin H. Vaidya, and Ram Ramanathan. Using directional antennas for medium access control in ad hoc networks. In *International Conference on Mobile Computing and Networking (MobiCom)*, pages 59–70. ACM Press, September 2002. ISBN 1-58113-486-X.

[2] E. Dijkstra. A Note on Two Problems in Connection with Graphs. *Numerical Mathematics*, 1:269–271, October 1959.

[3] Priyank Garg, Rushabh Doshi, Russell Greene, Mary Baker, Majid Malek, and Maggie Cheng. Using ieee 802.11e mac for qos over wireless. In *Proc. of International Performance Computing and Communications Conference (IPCCC)*, Phoenix, Arizona, April 2003. IEEE.

[4] Holger Karl and Andreas Willig. A short survey of wireless sensor networks. Technical Report TKN-03-018, Telecommunication Networks Group, Technische Universität Berlin, October 2003. This technical report also appeared as a contribution to the report

of the Working Group 2 “Ad hoc networks” of the Arbeitsgruppe Mobilkommunikation, DLR/BMBF.

[5] Phil Karn. Maca - a new channel access method for packet radio. In *Computer Networking Conference*, London, Ontario, Canada, September 1990. ARRL.

[6] Young-Bae Ko, Vinaychandra Shankarkumar, and Nitin H. Vaidya. Medium access control protocols using directional antennas in ad hoc networks. In *Proc. of Joint Conf. of Computer and Communications Societies (INFOCOM)*, Tel-Aviv, Israel, March 2000. IEEE.

[7] Kou Kobayashi and Masao Nakagawa. Spatially divided channel scheme using sectored antennas for csma/ca - directional csma/ca. In *Proc. of International Symposium on Personal, Indoor and Mobile Radio Communication (PIMRC)*, London, UK, September 2000. IEEE.

[8] J. Li, C. Blake, D: S. J. De Couto, H. I. Lee, and R. Morris. Capacity of ad hoc wireless networks. In *Proc. of International Conference on Mobile Computing and Networking*. ACM, August 2001.

[9] C.H.R. Lin and M. Gerla. Asynchronous multimedia multihop wireless networks. In *Proc. of Joint Conf. of Computer and Communications Societies (INFOCOM)*. IEEE, April 1997.

[10] En-Yi A. Lin, Adam Wolisz, and Jan M. Rabaey. Power-efficient rendez-vous schemes for dense wireless sensor networks. In *Proc. of International Conference on Communications (ICC)*, Paris, France, June 2004. IEEE.

[11] Asis Nasipuri, Shengchun Ye, and Robert E. Hiromoto. A MAC protocol for mobile ad hoc networks using directional antennas. In *Proc. of Wireless Communications and Networking Conference (WCNC)*, Chicago, IL, September 2000. IEEE.

[12] J.L. Sobrinho and A.S. Krishnakumar. Real-time traffic over the ieee 802.11 medium access control layer. In *Bell Labs Technical Journal*, volume 1, pages 172–187, Autumn 1996.

[13] N.H. Vaidya, P. Bahl, and S.Gupta. Distributed fair scheduling in wireless lan. In *Proc. of Conf. on Mobile Computing and Networking*. ACM, August 2000.

[14] Shugong Xu and Tarek Saadawi. Does the ieee 802.11 mac protocol work well in multihop wirelles ad hoc networks? *IEEE Communications Magazine*, June 2001.

[15] Wei Ye, John Heidemann, and D. Estrin. An energy-efficient mac protocol for wireless sensor networks. In *Proc. of Joint Conf. of Computer and Communications Societies (INFOCOM)*, New York, NY, June 2002. IEEE.