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Empirical Discussion on Directional MAC Protocols for Ad hoc Networks using Practice Smart Antennas

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***Abstract*-Recent studies on directional Media Access Control (MAC) protocols using smart antennas for wireless ad hoc networks have shown that directional MAC protocols outperform traditional omni-directional MAC protocols. Those studies evaluate performance primarily based on a simulations, where antenna beam is assumed to be ideal, i.e., with neither side-lobes nor back-lobes. Propagation conditions are also assumed to be based on a mathematical model without realistic fading. However, for the real application of ad hoc networks those optimistic assumptions do not hold anytime. In this paper, we develop at first a testbed for directional MAC protocols which enables investigation of the performance of MAC protocols in a real environment. It incorporates ESPAR as a practical smart antenna, IEEE802.15.4/ZigBee, GPS and gyro modules to allow easy installation of different MAC protocols. To our knowledge, it is the first compact testbed with a practical smart antenna for directional MAC protocols. We implement a directional MAC protocol called SWAMP to evaluate it in a real environment. The empirical discussion based on the experimental results shows the degradation of the protocol with ideal antennas, and it shows that the protocol still achieves the SDMA effect of spatial reuse and the effect of communication range extension.**

1. INTRODUCTION

Ad hoc networks [1] are an autonomous system of mobile nodes which share a single wireless channel to communicate with each other. Previous works on ad hoc networks assume the use of omni-directional antennas that transmit or receive signals equally well in all directions. Traditional MAC protocols, such as IEEE 802.11 DCF (Distributed Coordination Function) [2], are designed for omni-directional antennas and cannot achieve high throughput in ad hoc networks because they waste a large portion of the network capacity.

On the other hand, smart antenna technology may have significant potentials [3]. In particular, it can improve spatial reuse of the wireless channel, which allows nodes to communicate simultaneously without interference. Furthermore, the directional transmission concentrates signal power to the receiver, which enlarges the transmission range. Thus, it can potentially establish links between nodes farther away from each other, and it prevents network partitions and the number of routing hops can be fewer than those of omni-directional antennas.

However the potentials that smart antennas may have, a sophisticated MAC protocol is required to take advantage of these benefits in ad hoc networks. Recently, several directional MAC protocols, typically modifications of IEEE 802.11 DCF, have been proposed for ad hoc networks including our proposed MAC protocol called SWAMP [4]. SWAMP provides both spatial reuse of the wireless channel and communication range extension by two types of access modes that utilize the directional beam effectively, and it contains a method of obtaining the location information of its neighbors.

For use of the wireless devices, the performance of the proposed MAC protocol should be evaluated taking into consideration the effects of actual antenna patterns resulting from side-lodes and back-lobes, and actual propagation conditions including realistic fading. Thus at this time, we have developed a testbed for validation in a realistic environment, which is based on ESPAR antenna and IEEE802.15.4/ZigBee wireless module, and has a GPS (Global Positioning System) interface for utilizing location information MAC protocol. And we embedded SWAMP into this testbed and evaluated it in the actual environment.

As a testbed for mobile ad hoc networks or sensor networks, some experimental systems are available such as MICA MOTE [5] and U-cube [6]. Their target protocols are mainly on higher layer than routing. Neither is it easy to develop MAC protocols on the systems nor are they equipped with compact directional antennas.

This paper summarizes SWAMP protocol and provides an overview of the testbed. In addition, we analyze the experimental results of SDMA and the wider range of communication available due to SWAMP.

2. DIRECTIONAL MAC PROTOCOLS

Various MAC protocols using smart antennas or directional antennas, typically referred to as directional MAC protocols, have been proposed for ad hoc networks.

Ko et al. [7] proposed DMAC (Directional MAC) in which all frames are transmitted directionally except for the CTS (Clear To Send). Choudhury et al. [8] proposed MMAC (Multi-hop RTS MAC), which involves the multi-hop RTS (Request To Send) to take advantage of the higher gain obtained by directional antennas. These protocols, however,

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require various additional mechanisms to provide location information and to forward the RTS.

In [9] [10] and [11], RTS is transmitted omni-directionally in order to find the receiver in case location information is not available. Each node estimates the direction of neighboring nodes for pointing the beam with AOA (Angle of Arrival) when it hears any signal. Because these protocols employ at least one omni-directional transmission, the coverage area provided by directional transmissions is limited because the protocols cannot exploit one of the main benefits of directional antennas, i.e., increased transmission range.

Ramanathan [12] proposes circular directional transmission of periodic hello packets to obtain node information that is located away from the omni-directional transmission range. Korakis et al. [13] proposed circular RTS, which scans the area around the transmitter to find the addressed receiver, correcting the deafness and the hidden-terminal problems that arise from directional transmissions. Bandyopadhyay et al. [14] developed additional frames in order to determine the neighbor topology by recording the angle and signal strength. Although these schemes attempt to extend communication range, circular transmission increases the delay and incurs large control overhead.

3. SWAMP

SWAMP is based on IEEE 802.11 DCF and utilizes the directional beam effectively to increase spatial reuse and extend the transmission range. SWAMP consists of two access modes; OC-mode (Omni-directional transmission range Communication mode) and the EC-mode (Extend omni-directional transmission range Communication mode).

3.1 Antennas Models

SWAMP provides four antenna beam forms. Fig. 1 illustrates four beam forms and each form's transmission range. Note that in the figure, nodes can communicate when the transmitting beam and the receiving beam are at least tangential to each other. OB (omni-directional beam form) and DL (directional low gain beam form) are used for regular link communication in the OC-mode, while DM (directional middle gain beam form) and DH (directional high gain beam form) are used for extended link communication in the EC-mode.

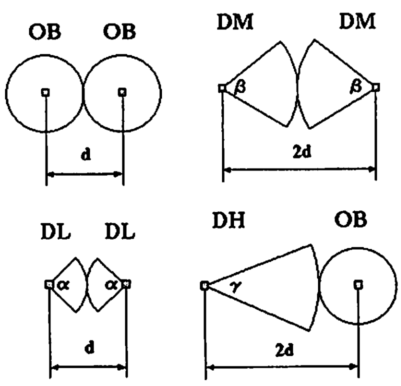

Figure 1: Smart antenna beamforming.
Left side: Transmitting beamforming
Right side: Receiving beamforming

3.2 OC-mode

Fig. 2 illustrates the OC-mode frame sequence with the corresponding beams. The OC-mode is selected when the receiver is located within the range of omni-directional transmission, or when the transmitter has no knowledge of the receiver. The RTS/CTS handshaking attempts to reserve the wireless channel and to exchange the location information between the transmitter and the receiver. Then, these nodes forward the location information that is obtained by the reception of the RTS or CTS to neighbors as NHDI (Next Hop Direction Information) using omni-directional CTS or SOF (Start of Frame). NHDI is registered in the NHDI table of each node and this information is used in EC-mode. DATA and ACK are sent by DLs that point beams towards each other. Omni-NAV (Network Allocation Vector), which is shorter than ordinal NAV, is used to increase simultaneous communications and the spatial reuse of the wireless channel.

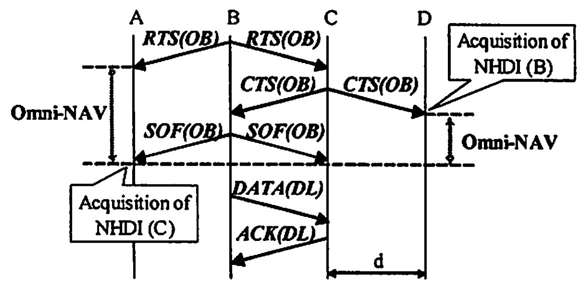

Figure 2: OC-mode frame sequence (B to C).

3.3 EC-mode

Fig. 3 illustrates the EC-mode frame sequence with the corresponding beam. The EC-mode is selected when the receiver has already been registered in the transmitter's NHDI table. Because the transmitter has prior knowledge of the direction of the intended receiver, the transmitter can determine the necessary direction to point the beam towards the receiver. To perform communications between nodes at a distance of 2d, RTS is required to use the high gain beam form (DH) because the receiver waits for signals with the omni-directional beam form (OB) in an idle state. After the transmitter sends RTS, it switches the beam form from DH to DM. After the receiver receives RTS, it also switches the beam form from OB to DM and points the beam towards the transmitter. When the transmitter fails to gain EC-mode access beyond the EC-retry limit, the transmitter deletes the receiver information from its own NHDI table. In the EC-mode, DNAV (Directional NAV) [9] is used instead of NAV for virtual carrier sensing.

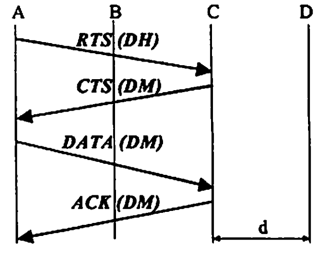

Figure 3: EC-mode frame sequence (A to C)

4. TESTBED

We have developed a compact wireless ad hoc network testbed for validation of MAC protocol in a realistic environment, which is based on an ESPAR antenna and an IEEE802.15.4/ZigBee wireless module.

4.1 ESPAR Antenna

An ESPAR antenna is a smart antenna, which can form omni-directional or directional beam patterns. An example of the specific structure is shown Fig. 4. With a vertical monopole at the center, several parasitic elements are circularly arrayed in its vicinity. The parasitic elements may be called non-excited elements, or non-fed elements, and are not directly connected to the feed circuit. They are electromagnetically coupled in space with the center element and other parasitic elements. At the bottom of each parasitic element, a variable capacitance diode (varactor) is inserted in series and is grounded. A DC bias voltage is applied to each varactor via an RF choke or a large resistor. In contrast to the conventional phased array antenna in which the weight vector (amplitude and phase) for each element is directory controlled, the ESPAR antenna does not have a weight circuit. Instead, the capacitance of the varactor loading the parasitic element is controlled. The ESPAR antenna differs fundamentally from the conventional phased array antenna in the following three aspects:

(1) one feed system
(2) Inter-element coupling is the basis of beam formation, and
(3) Varactors are connected directly to the parasitic elements.

The RF signal is fed to the center element. Hence, only one transmitting and one receiving circuit are needed. By controlling the reactance value of the varactor by applying the DC bias voltage, beams with various radiation patterns are formed in the horizontal plane. Since these bias voltages are opposed to those of the variable capacitance diodes, no DC current flows under this voltage controlled operation. Therefore, the parasitic elements do not consume the DC and RF energies. Compared to the conventional phased array antenna in which the radiating elements and the variable phase shifters are designed separately, the ESPAR antenna hardware configuration is substantially simplified. Hence, a variable radiation pattern can be obtained at low cost and with low power consumption [15].

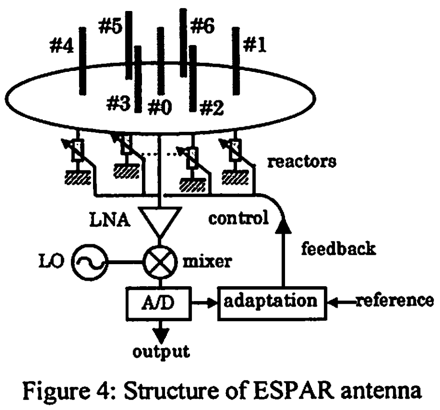

Figure 4: Structure of ESPAR antenna

4.2 IEEE802.15.4/ZigBee wireless module

When designing a testbed for embedding a proposed MAC protocol, it is important to choose a suitable type of wireless module. A suitable wireless module should have open source driver software so it can be modified to operate under the proposed MAC protocol. The current driver software for IEEE802.11 wireless LAN a/b/g is closed source, so its driver software cannot be modified without a special contract with the chip maker. The driver software in IEEE802.15.4/ZigBee is open source, the specifications for its PHY and MAC layer have been authorized as international standards, and its network and application layer are currently offered as a standard in the ZigBee alliance. Although 250 Kbps data transmission rate of ZigBee is too small when compared with that of WLAN, a modification to the ZigBee driver software is available at low cost and low DC current consumption, which led us to choose ZigBee as the wireless module for the testbed. The general specification of ZigBee chip CC2420 (manufactured by Chipcon company) is shown in Table 1.

In the design of the software for embedding the proposed MAC protocol, the program library for controlling hardware of the ZigBee chip includes carrier sense level adaptation, ESPAR antenna beam management, Tx power controlling, time-count and so on. Of particular interest is the function of Tx power controlling (25dBmax dynamic range) which benefits the coordination of the EIRP (Effective Isotropic Radiation Power) between omni-directional beam and directional beam.

Table 1: ZigBee: Chipcon CC2420

No.	Item	Specification
1	Tx power	1mW
2	Modulation	Offset-QPSK
3	SS process	DS-SS
4	SS rate	2Mchips

4.3 System configuration

The wireless ad hoc network testbed consists of a notebook PC for command of data communication and a data log collection of retry numbers, contention numbers and so on, an ESPAR antenna as a smart antenna, a ZigBee wireless module, and a GPS and gyro for collecting location information collection. An Overview of the testbed is shown in Fig. 5.

When we embedded the proposed MAC protocol, SWAMP on a ZigBee wireless module, we adopted all the frames of SWAMP into the ZigBee data frame without the ZigBee control frame as a beacon. The SWAMP frame, including the control frame (RTS/CTS/SOF) and data frame (DATA/ACK), should be taken as a capsule into the data payload of the ZigBee data frame. When data size is over the maximum data payload size of 116 bytes, plural data frames are transmitted continuously. Configuration of the ZigBee data frame including SWAMP frame (control or data) is shown in Fig. 6.

The minimum received signal level of 5 min was measured at a -92dBm at 250Kbps fixed data rate with the description of 10% packets error rate at 500 times average data transmission on a coaxial wire line and variable attenuators without effect of fading. Measured packet error rate vs. RSSI is shown in Fig. 7.

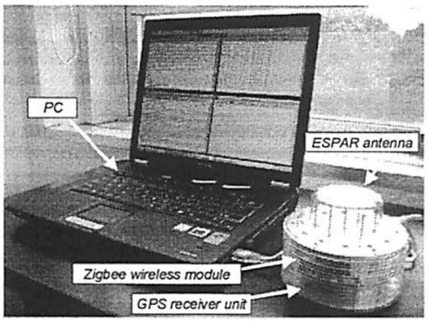

Figure 5: Overview of the testbed

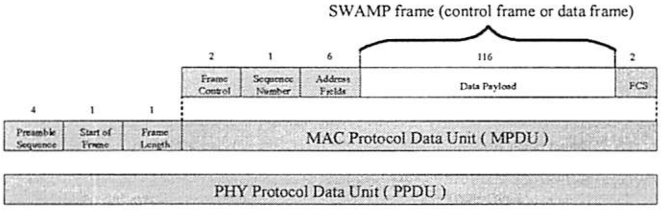

Figure 6: Configuration of the ZigBee data frame including SWAMP frame (control frame or data frame)

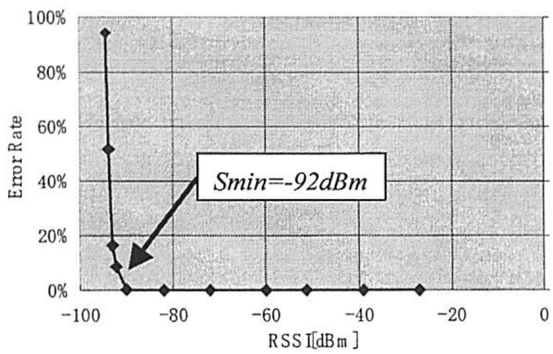

Figure 7: Measured packet error rate vs. RSSI

5. SWAMP Experiment

5.1 OC-mode evaluation

SWAMP OC-mode is expected for SDMA, which allows nodes to communicate simultaneously. Nevertheless, the ESPAR antenna has side-lobes and back-lobes, in which the gain is about 10dB less than that of directional main beam, which increases the probability of interference over that of the ideal directional antenna pattern. The actual ESPAR antenna pattern is shown in Fig. 8. Absolute antenna gains are 2dBi at the omni-directional beam and 6dBi at the directional main beam.

We prepared 4 nodes consisting of two communication pairs situated on the line. The layout for 4 Nodes is shown in Fig. 9. The larger sector signifies the directional main beam, the smaller sector signifies the back-lobe and the circle line signifies the omni-directional beam. In either case of communication pairs, the distance between two nodes (node 1 to node 2, and node 3 to node 4) is situated at 6m due to the actual limitations in the park.

At the SWAMP OC-mode, Tx power is controlled to be the same EIRP between the omni-directional beam and directional beam. In the actual field, we confirmed the same maximum communication distance of 80m when Tx power control levels were -14dB attenuator with each omni-directional beam and -25dB attenuator with each directional beam. The attenuator difference was 11dB, which includes small correction 3dB, which was different than the calculated 8dB, amounting to twice (Tx and Rx) the antenna gain difference between the omni-directional beam of 2dBi and the directional beam of 6dBi. RSSI fluctuation often occurs due to the effect of fading and multipath in the actual field, which requires a certain amount of correction between the measured and calculated values. Example data for RSSI vs. communication distance is shown in Fig. 10. Experiment conditions in the park included antenna height at 55cm, Tx power at 0dBm without attenuation, and consideration of items on the ground including stones and grass and so on. RSSI under multipath is calculated by equation (1).

$$P_r = P_t G_t G_r \left[D_d \left(\frac{\lambda}{4\pi r_d} \right) + D_r \left(\frac{\lambda}{4\pi r_r} \right) \Gamma v e^{-j\{k(r_d - r_r) + \phi\}} \right]^2 \quad \cdots\cdots (1)$$

Where Pr is the received signal level, Pt is the transmitter power, Gt and Gr are the Tx and Rx boresight antenna gains, Dd and Dr are the direct wave and reflection wave directivities with respect to the Tx and Rx antennas, r_d and r_r are the optical path lengths of the direct wave and reflection wave from the ground, k is $2\pi/\lambda$, and Φ and Γv are the phase delay and reflection factors (electric field polarization) [16].

According to the results of the experiment, RSSI fluctuated in a width including max. 7dB deviation from what was calculated. Maximum communication distance including 3dB correction with several antenna pattern combinations each other is shown in Table 2.

Either way the omni-directional and directional beam antenna patterns are combined, we measured each throughput in proportion to the distance (X) between the 2 communication pairs. The experimental conditions included CBR125kbps, packet size of 512byte, and other parameters are shown in Table 2. The result of the experiment is shown in Fig. 11. In each combination of omni-directional beams, throughput degradation occurred at ranges of less than 80m due to interference between each omni-directional beam, which agrees with the results shown in Table 2. On the other hand, in each combination of directional beam, throughput degradation occurred at ranges of less than 20m due to interference with the directional main beam and back-lobe. This 20m plus 6m (the distance between two nodes in a communication pair) equals 26m, which is close to 25m, which agrees with the results shown in Table 2. While the two nodes should be set at a distance of 80m from each other in a communication pair, interference distance (X) is possible at 8m, which is the max. communication distance between the back-lobes shown in Table 2.

Therefore, according to the results of the experiment, we have verified the superiority of SDMA with directional beams over that of SDMA with omni-directional beams.

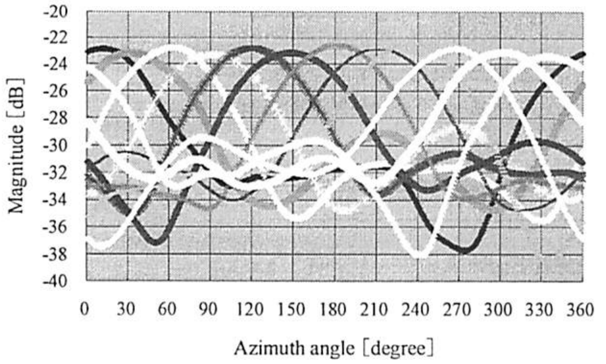

Figure 8: ESPAR antenna pattern

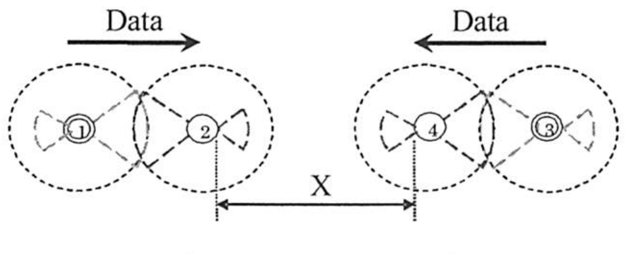

Figure 9: Layout for 4 Nodes

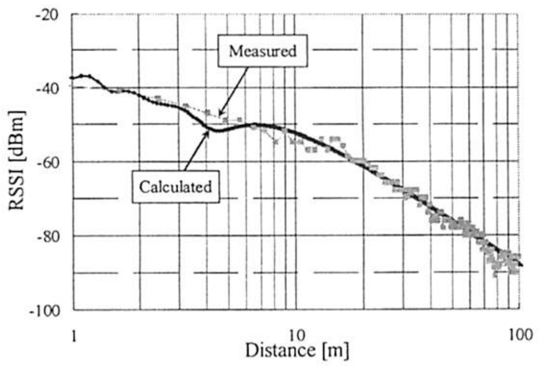

Figure 10: RSSI vs. communication distance

Table 2: Maximum communication distance

No.	Item	Sector-Sector			Omni-Omni	-
		Back-Back	Back-Main	Main-Main		
f	Frequency	2.405	2.405	2.405	2.405	GHz
Pt	Tx power control	-25	-25	-25	-14	dBm
Lt	Tx loss	-2	-2	-2	-2	dB
Gt	Tx antenna gain	-4	6	6	2	dBi
PtGt	EIRP	-31	-21	-21	-14	dBm
R	Max. comm. distance	8	25	80	80	m
—	Propagation loss	-58.1	-68.0	-78.1	-78.1	dB
Gr	Rx antenna gain	-4	-4	6	2	dBi
Lr	Rx loss	-2	-2	-2	-2	dB
Pr	Received signal level	-95	-95	-95	-92	dBm
Smin	Min. received siganal level	-92	-92	-92	-92	dB
—	Correction (Pr-Smin)	-3	-3	-3	0	dB

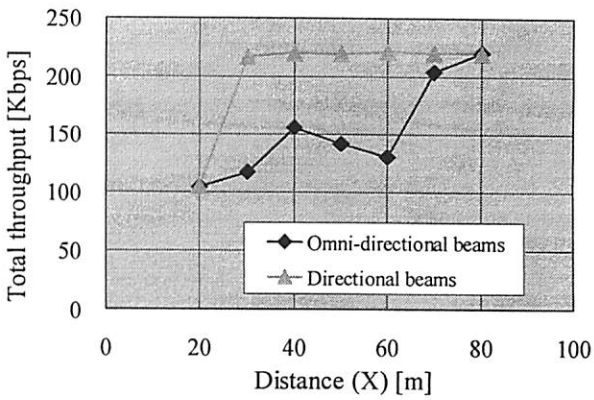

Figure 11: Throughput vs. distance (X)

5.2 EC-mode evaluation

The SWAMP EC-mode is expected for wider range communication, focusing its Tx power concentration in a directional beam towards the receiver node.

We prepare three nodes situated in a triangle, the formation of which is shown in Fig. 12. Node A and node C are located at almost the same distance from node B, so that the distance between node A and node C is longer than the distance of node A to node B or node B to node C. The experiment assumes that node B is Tx in OC-mode with node C, node ACis Tx in EC-mode with node C and node C is always Rx at both modes.

When operating SWAMP, the OC-mode operation should be executed before EC-mode operation. In the OC-mode, while node C is situated to allow communication with node B but is unable to communicate with node A because it is too far away as mentioned above, node A is unaware of node C's location information. In the EC-mode, after node B transmits an SOF packet including node C's location information to node A in the OC-mode communication between node B and node C, node A is then able to communicate with node C in the EC-mode.

We measured the received packet numbers vs. time in the OC-mode and EC-mode simultaneously in the situation shown in Fig. 12. Experiment conditions includes CBR125kbps, packet size of 512byte, Tx power control levels in the OC-mode equal to those shown in Table 2, and operation in EC-mode without attenuator with directional beam. By adjusting the node communication distance, measured RSSI in OC-mode is -89dBm, and in EC-mode it is -69dBm, including about ±3dB fluctuation. The result of this experiment is shown in Fig. 13. Node A cannot communicate with node C until OC-mode communication starts between node B and node C. Once, node A receives an SOF packet from node B in the OC-mode, node A can start communicating with node C in the EC-mode after the passage of about 44sec., as shown in Fig. 13.

Therefore, according to the results of the experiment, we have confirmed that a wider range communication is possible with directional beams in the EC-mode than that of the OC-mode operation due to transmission of SOF packets in the OC-mode.

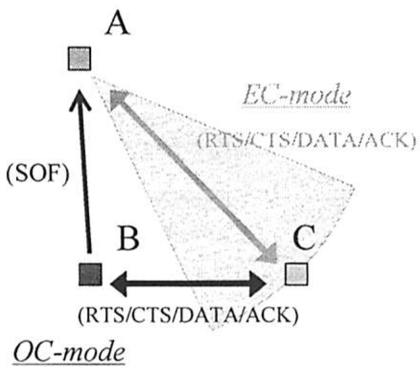

Figure 12: Situation for EC-mode evaluation

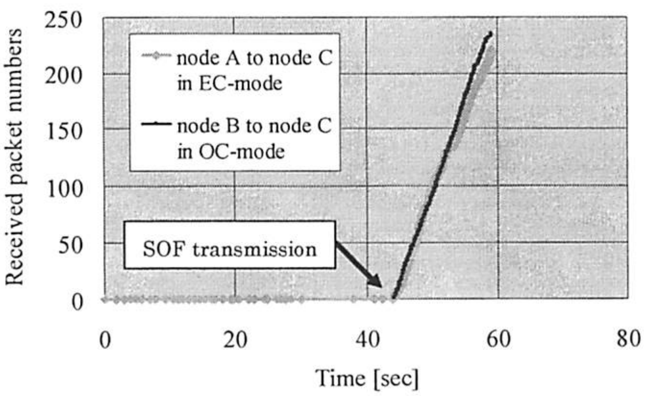

Figure 13: Received packet numbers vs. time

6. Conclusion

We have developed a compact wireless ad hoc network testbed based on an ESPAR antenna and an IEEE802.15.4/ZigBee wireless module, which allows easy installation of different MAC protocols. We designed a program library on the driver software for controlling the ZigBee hardware and embedded a directional MAC protocol, SWAMP, into the testbed for validation in a realistic environment.

According to the results of the experiment, SWAMP operating in the OC-mode has shown the superiority of an SDMA with directional beams over SDMA with omni-directional beams, even if the ESPAR antenna includes side-lobes and back-lobes. In either antenna pattern combination, including omni-directional beams and directional beams, measured interference distances agreed well with the calculated distance. The SWAMP EC-mode has proven to extend the distance of communication, even if nodes are unable to communicate in the OC-mode because the packets cannot reach a longer distance. Once transmission of SOF packets in the OC-mode leads to communication in the EC-mode, a wider range communication may be established.

7. Acknowledgment

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