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Chapter 6

RANDOMIZED OVERHEARING TO IMPROVE ROUTING AND ENERGY PERFORMANCE IN MOBILE AD HOC NETWORKS*

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Abstract

Since data transmission in wireless mobile ad hoc network (MANET) is broadcast in nature, every node receives or overhears every data transmission occurring in its vicinity. Some MANET routing protocols such as Dynamic Source Routing (DSR) exploit this feature to collect route information via overhearing. However, it poses a challenging problem when a power saving mechanism (PSM) such as the one specified in IEEE 802.11 is employed, where a packet advertisement period is separated from the actual data transmission period. When a node receives an advertised packet that is not destined to itself, it switches to a low-power state during the data transmission period, and thus, conserves power. Allowing no overhearing may critically deteriorate the performance of the underlying routing protocol, while unconditional overhearing may offset the advantage of using PSM. This chapter proposes a new communication mechanism, called RandomCast or Rcast, via which a sender can specify the desired level of overhearing in addition to the intended receiver. Therefore, it is possible that only a random set of nodes overhear and collect route information for future use. Extensive simulation using the ns-2 network simulator shows that Rcast improves not only the energy efficiency, but also the energy balance among the nodes compared

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to the original IEEE 802.11 PSM and another recent similar mechanism, called On-Demand Power Management (ODPM) protocol.

Keywords: energy balance, energy efficiency, mobile ad hoc networks, network lifetime, overhearing, power saving mechanism.

1 Introduction

Energy conservation is one of the most critical issues in *mobile ad hoc networks* (MANETs). For this reason, many radio hardwares support low-power states, where substantially less amount of energy is consumed by limiting the normal communication activity [1]. For instance, the Lucent IEEE 802.11 WaveLAN-II consumes 1.15W and 0.045W in the idle-listening and low-power state, respectively [1], and the radio transceiver TR 1000 [2], used in Berkeley Motes [3], consumes 13.5mW and 0.015 mW, respectively. Therefore, in order to maximize the energy savings, it is important to turn off the radio or switch it to a low-power sleep state when nodes do not actively transmit or receive signals. IEEE 802.11 standard, which is the most popular wireless LAN standard, supports the power management function in its *medium access control* (MAC) layer specification [4]. Each mobile device can be in one of the two power management modes: *active mode* (AM) or *power save* (PS) mode. A device in the PS mode periodically wakes up during the packet advertisement period, called *Ad hoc (or Announcement) Traffic Indication Message* (ATIM) window to see if it has any data to receive. It puts itself into the low-power state if it is not addressed, but stays awaken to receive any advertised packet otherwise.

However, the IEEE 802.11 Power Save Mechanism (PSM) is difficult to employ in a multihop MANET because some routing MANET protocols such as *Dynamic Source Routing* (DSR) [5] assume that every node is able to receive or overhear every data transmission occuring in its vicinity. A major concern in integrating the DSR protocol with the IEEE 802.11 PSM is *overhearing*. Overhearing improves the routing efficiency in DSR by eavesdropping other communications and gathering route information. It incurs no extra cost if all mobile nodes operate in the AM mode because they are always awake and idle listening anyway. However, if mobile nodes operate in the PS mode, it brings on a high energy cost because they should not sleep but receive all the routing and data packets transmitted in their vicinity. A naive solution is to disable overhearing and let a node receive packets only if they are destined to it. However, it is observed that this solution reduces network performance significantly because each node gathers less route information due to the lack of overhearing, which in turn incurs a larger number of broadcast flooding of *route request* (RREQ) messages resulting in more energy consumption[1]. In summary, overhearing plays an essential role in disseminating route information in DSR but it should be carefully redesigned if energy is a primary concern.

This chapter proposes a message overhearing mechanism, called *RandomCast or Rcast*, via which a sender can specify the desired level of overhearing when it advertises a packet.

[1] This is what happens with Ad-hoc On-demand Distance Vector (AODV) [6], which is another popular on-demand routing algorithm. AODV takes a conservative approach to gather route information: It does not allow overhearing and eliminates existing route information using timeout. However, this necessitates more RREQ messages. According to Das et al., 90% of the routing overhead comes from RREQ in [7].

Upon receiving a packet advertisement during an ATIM window, a node makes its decision whether or not to overhear it based on the specified overhearing level. If *no overhearing* is specified, every node decides not to overhear except the intended receiver and if *unconditional overhearing* is specified, every node should decide to overhear. *Randomized overhearing* achieves a balance somewhere in between, where each node makes its decision probabilistically based on network parameters such as node density and network traffic. Rcast helps nodes conserve energy while maintaining a comparable set of route information in each node. Since route information is maintained in the *route cache* in DSR, Rcast effectively avoids unnecessary effort to gather redundant route information and thus saves energy. The key idea behind the Rcast scheme is to explore the temporal and spatial locality of route information, as is done in the CPU cache. Overheard route information will probably be overheard again in the near future and thus it is possible to maintain the same quality of route information, while overhearing only a small fraction of packets. Even though a node misses a particular route information, it is highly probable that one of its neighbors overhears it and can offer the information when the node asks for it. Note that we have chosen DSR in this chapter because other MANET routing algorithms usually employ periodic broadcasts of routing-related control messages, such as link states in *table driven protocols* or *Hello* messages in AODV [6], and thus tend to consume more energy with IEEE 802.11 PSM.

The performance of the proposed Rcast scheme is evaluated using the ns-2 network simulator [8]. According to the simulation results, the proposed algorithm reduces the energy consumption as much as 236% and 131% compared to the original IEEE 802.11 PSM and *On-Demand Power Management* (ODPM) [9] protocol, which is one of the competitive schemes developed for multihop networks, respectively, at the cost of at most 3% reduction in packet delivery ratio. It is also found that Rcast improves the energy balance among the nodes and increases the network lifetime. Simulation results indicate that variance of energy consumption of nodes is four times higher in ODPM than in Rcast. Note that the concept of Rcast can also be applied to broadcast messages in order to avoid redundant rebroadcasts, as studied by Ni et al. [10] and thus can usefully be integrated with other MANET routing algorithms.

The rest of the chapter is structured as follows. Section 2 presents the background and the related work on the PSM of IEEE 802.11 and DSR routing protocol. Section 3 presents the proposed Rcast scheme and its use with DSR, while Section 4 is devoted to extensive performance analysis. Section 5 draws conclusions and presents future directions of this study.

2 Background and Related Work

We assume that mobile nodes operate as the IEEE 802.11 PSM for energy-efficient medium access and use DSR for discovering and maintaining routing paths. Section 2.1 summarizes the DSR routing protocol with an emphasis on *route cache*. It also discusses the stale route and load unbalance problem in DSR and argues that unconditional overhearing is the main reason behind them. Section 2.2 explains the IEEE 802.11 PSM and previous research work on its use in multihop networks.

2.1 DSR Routing Protocol

2.1.1 Route Discovery and Maintenance

Route cache is one of the most important data structures in DSR and is used to reduce the routing-related control traffic. When a node has a data packet to send but does not know the routing path to the destination, it initiates the route *discovery procedure* by broadcasting a control packet, called *route request packet* (RREQ). When a RREQ reaches the destination, it prepares another control packet, called *route reply packet* (RREP) and replies back to the source with the complete route information. Upon receiving a RREP, the source begins transmitting the data packets to the destination, and it saves the route information in its route cache for later use.

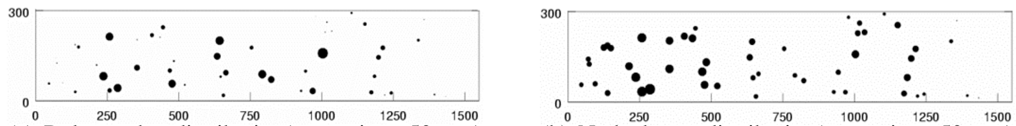
Since data transmission in wireless networks is broadcast in nature, intermediate relaying nodes as well as other nearby nodes also learn about the path to the destination via overhearing. Therefore, the number of RREQ packets can be minimized because a node may have cached the path to a destination in its route cache. Route caching reduces the number of RREQ packets even further by allowing an intermediate node to reply to a RREQ if it has the destination route information. This mitigates network-wide flooding of RREQ packets and also saves energy significantly.

Since nodes move randomly in a MANET, link errors occur and a route information that includes a broken link becomes obsolete. When a node detects a link error during its communication attempt, it sends a control packet, called *route error packet* (RERR), to the source and deletes the stale route from its route cache. In addition. RERR informs nearby nodes about the faulty link so that they can also delete the path including the broken link.

2.1.2 Stale Route Problem in DSR

However, since link errors (or RERR) are not propagated “fast and wide”, as pointed out by Marina and Das [11], route caches often contain stale route information for an extended period of time. In addition, the erased stale routes are possibly un-erased due to in-flight data packets carrying the stale routes. When a node has an invalid route in its route cache or receives a RREP that contains an invalid route, it would attempt to transmit a number of data packets without success while consuming energy. Hu and Johnson studied design choices for route cache in DSR and concluded that there must be a mechanism, such as *cache timeout*, that efficiently evicts stale route information [12].

While the main cause of the stale route problem is node mobility, it is unconditional overhearing that dramatically aggravates the problem. This is because DSR generates more than one RREP packets for a route discovery to offer alternative routes in addition to the primary route to the source. While the primary route is checked for its validity during data communication between the source and the destination, alternative routes may remain in route cache unchecked even after they become stale. This is the case not only for the nodes along the alternative routes, but also for all their neighbors because of unconditional overhearing.



(a) Role number distribution(pause time=50 sec.) (b) Node degree distribution(pause time=50 sec.)

Figure 1: Node degree and role number distribution (AODV, 50 nodes in 1550 $\times$ 300 m^2 area).

2.1.3 Load Unbalance Problem in DSR

On-demand routing algorithms such as DSR exhibit another undesirable characteristic, called load unbalance. In a multihop mobile network, each node plays an important role as a router to forward packets on other nodes' behalf. In an ideal case, each mobile node takes equal responsibility of packet forwarding to others. However, it is observed that this is not usually the case and several troubles may arise due to over-dependence of packet forwarding functionality on a few overloaded nodes [13]. For example, overloaded nodes can exhaust their battery power much faster than other nodes and critically decrease the network lifetime.

To quantitatively measure the packet forwarding responsibility, *role number* of a node is defined as a measure of the extent to which the node lies on the paths between others. It can be calculated by examining each node's route cache to find all intermediate nodes stored during all packet transmissions. The role number is considered as a measure of the influence, or utility of a specific node when forwarding packets in a network. Fig. 1 shows the simulation results based on ns-2 simulator [8]. Ad-hoc On-Demand Distance Vector (AODV) routing algorithm [6] and 40 CBR sources with three 512 byte packets/second are simulated. Random waypoint model is used with node speed between 0 to 20 meters/second and pause time of 50 seconds during the 900 seconds of simulation period. Fig. 1(a) depicts the role numbers, represented by the size of the circle. It can be easily shown that mobile nodes do not exhibit uniform role numbers across the network, meaning that there is a significant load unbalance problem. A further investigation suggests that it is not correlated with node degree as contrary to our initial expectation, which is shown in Fig. 1(b). It is argued in [13] that the non-uniform load distribution is caused primarily by "*preferential attachment*" [14] in the dynamics of route information construction in route caches, together with the *expand ring search* algorithm used in DSR protocol. For example, suppose a node, say node S, has route information to a number of destination nodes. When a neighboring node, say node T, wishes to discover a route to one of those destinations, node S would supply the desired information to node T. Thus, node S becomes an intermediate node for the route from node T to the destination and node S will have an additional entry from S to node T. In other words, an overloaded node becomes more overloaded with time due to unconditional overhearing.

2.2 Power Saving Mechanism (PSM) in IEEE 802.11

In this chapter, we assume that the network layer software, DSR, interacts with a lower layer protocol conforming to the IEEE 802.11 standard [4]. According to its specification, there are two modes of operation depending on the existence of an access point (AP). These are referred to as the *Distributed Coordination Function* (DCF) and the *Point Coordination Function* (PCF). The DCF uses a contention algorithm to provide access to all traffic based on the *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) and delay, known as *InterFrame Space* (IFS). The PCF is an optional access method implemented on top of the DCF and provides a contention-free service coordinated by an AP. In the PCF, an AP has a higher access priority than all other mobile nodes, and thus, it not only sends downlink packets but also controls uplink packets by polling stations [15].

2.2.1 IEEE 802.11 PSM in One-hop Networks

Power saving in PCF mode is achieved by the coordination of the AP, which operates in AM. The AP periodically sends beacon signals to synchronize other mobile nodes that operate in the PS mode and informs them whether they have packets to receive or not using the *Traffic Indication Map* (TIM), which is included in the beacon in the form of a bitmap vector. If a node is not specified as a receiver in the TIM, it switches off its radio subsystem during the data transmission period.

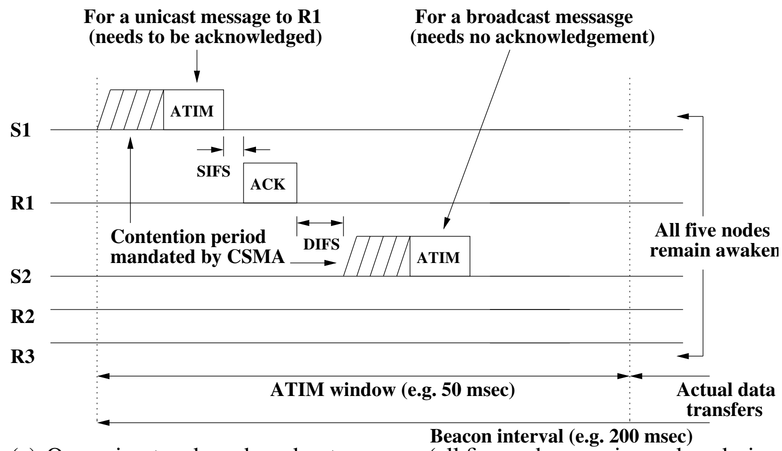
In the DCF, power saving is more difficult to achieve. In the absence of an AP, nodes in the PS mode should synchronize among themselves in a distributed way[2]. In addition, a beacon does not contain the TIM any more and each sender should advertise its own packet by transmitting an ATIM frame during the packet advertisement period, called *ATIM window*. Each packet is buffered at the sender and is directly transmitted to the receiver during the data transmission period.

Fig. 2 shows the PSM protocol in the DCF with an example mobile network of five nodes, S_1, R_1, S_2, R_2, and R_3. In Fig. 2(a), node S_1 has a unicast packet for node R_1 and node S_2 has a broadcast packet. They advertise them during the ATIM window. Note that nodes S_1 and S_2 compete with each other using the same CSMA/CA principle for transmitting the ATIM frames. Node S_1 needs acknowledgment from node R_1 but node S_2 does not. In this scenario, all five nodes remain awaken during the data transmission period in order to receive the unicast and/or broadcast packets. Consider another example in Fig. 2(b). Here, node S_2 also has a unicast packet to R_2, and thus nodes S_1, R_1, S_2, and R_2 must be awaken, but node R_3 can switch to the low-power sleep state immediately after the ATIM window, because it does not have any packet to receive. It is important to note that node R3 should remain awaken if the unconditional overhearing is used.

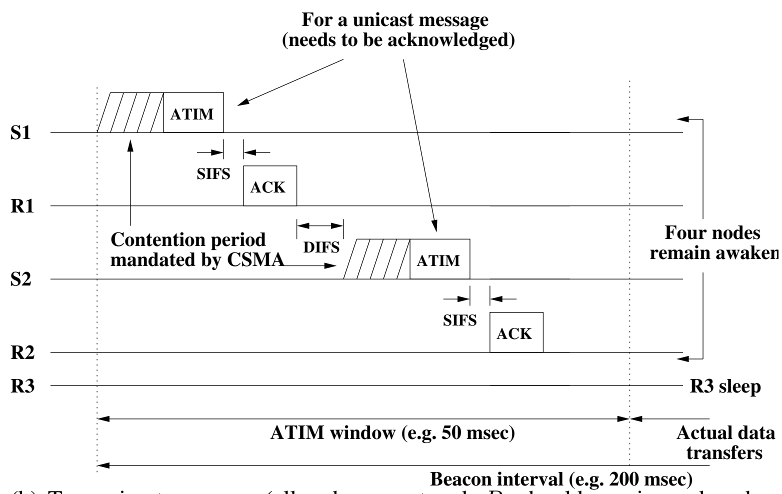
2.2.2 IEEE 802.11 PSM in Multihop Networks

Note that PSM in both PCF and DCF assumes that every node is within every other's radio transmission range. Thus, they are not directly applicable in multihop mobile networks. Recently, this problem has been addressed by a number of research groups. SPAN [18] mandates a set of nodes to be in AM, while the rest of the nodes stay in the PS mode. AM nodes offer the routing backbone so that any neighboring node can transmit to one of them

[2]Tseng et al. [16] and Huang and Lai [17] studied the clock synchronization problem. We do not discuss this issue in detail in this chapter and assume that all mobile devices operate in synchrony using one such algorithm.



(a) One unicast and one broadcast message (all five nodes remain awaken during the entire beacon interval)



(b) Two unicast messages (all nodes except node R_3 should remain awaken during the beacon interval)

Figure 2: IEEE 802.11 PSM (SIFS: Short IFS, and DIFS: DCF IFS).

without waiting for the next beacon interval. A drawback of this scheme is that it usually results in more AM nodes than necessary and degenerates to all AM-node situation when the network is relatively sparse. More importantly, it does not take the routing overhead into account because it uses the geographic routing and assumes that location information is available for free. This is neither realistic nor compatible for use with DSR or AODV as pointed out in [19].

Zeng and Kravets suggested a similar approach, called *On-Demand Power Management* (ODPM) [9], in which a node switches between the AM and PS modes based on communication events and event-induced timeout values. For example, when a node receives a RREP packet, it is better to stay in AM for more than one beacon interval (timeout) hoping that there will be more data packets to be delivered in the near future. This scheme asks for each node to switch between the AM and PS modes frequently, which may incur non-negligible overhead. It may reduce the packet delay by transmitting data packets immediately if the receiver is believed to be in AM. However, obtaining neighbors' power management mode is not trivial. This requires either an additional energy cost to obtain it or an extended packet delay if it is not accurate. Also, its performance greatly depends on timeout values, which need fine tuning with the underlying routing protocol as well as traffic conditions. For example, consider that a node stays in AM for five consecutive beacon intervals upon receiving a data packet as is assumed in [9]. If data traffic occurs infrequently, say once every six beacon intervals, the node stays in AM for five intervals without receiving any further data packets and switches to low-power sleep state. It receives the next data packet while operating in the PS mode, and thus, decides again to stay five intervals. Packet delay is not affected but it consumes more energy than unmodified IEEE 802.11 PSM.

2.2.3 Gossiping

Recently, there has been an active research on a probabilistic protocol, called as a *gossiping* [20, 21, 22, 23, 24, 25], which has a potential to be used with PSM. The gossiping decides whether a node forwards a packet with a certain probability, a *gossiping probability*, to reduce a number of routing packets in a network, and has been widely applied to wired/wireless networking applications. In particular, various gossiping techniques have been suggested in mobile ad hoc networks [20, 23] and sensor networks [24, 25], because traditional flooding may incur the broadcast storm problem [10] and consume a serious amount of energy. Thus, they try to minimize a number of forwarded routing packets without degrading of network performances.

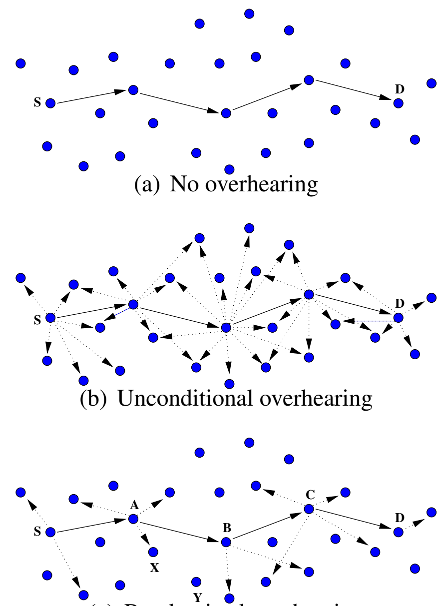
Hass et al. [23] suggest a couple of gossiping schemes with a pre-determined gossiping probability, and incorporate them into AODV routing protocol. In [24], they propose an adaptive gossiping for a time-varying network topology by considering a dependency among the nodes. Each node maintains a list of nodes (parent, child, and sibling nodes) that depend on this node for packet forwarding. However, the list is easily obsoleted due to node mobility and frequent updates of the list may incur a large overhead. More inportantly, the potential to combine with the existing IEEE 802.11 PSM and DSR protocol is not yet realized, which is the main goal of the proposed protocol in this chapter.

3 Randomized Overhearing Using Rcast

This Section describes the *RandomCast* or *Rcast*-based communication mechanism, aimed at improving the energy performance by controlling the level of overhearing without a significant impact on network performance. Compared to the algorithms in Section 2.2, the proposed scheme assumes that the mobile nodes consistently operate in the the PS mode and employ the DSR routing algorithm [5]. Section 3.1 presents the basic idea of Rcast and its advantages. Sections 3.2 and 3.3 discuss the implementation of Rcast and its integration with DSR, respectively.

3.1 No, Unconditional, and Randomized Overhearing

As explained in Section 2.2, a unicast packet is delivered only to an intended receiver if the IEEE 802.11 PSM is employed. Consider that a node S transmits packets to a node



(a) No overhearing

(b) Unconditional overhearing

(c) Randomized overhearing

Figure 3: Delivery of a unicast message with different overhearing mechanisms.

D via a pre-computed routing path with three intermediate nodes as shown in Fig. 3(a). Only five nodes are involved in the communication and the rest would not overhear it (*no overhearing*). However, if each neighbor is required to overhear as in DSR, each sender should be able to "broadcast" a unicast message. i.e., it specifies a particular receiver but at the same time asks others to overhear it as shown in Fig. 3(b) (*unconditional overhearing*).

Randomized overhearing adds one more possibility in between unconditional and no overhearing. As shown in Fig. 3(c), some of the neighbors overhear, but others do not and these nodes switch to the low-power state during the data transmission period. Randomized overhearing saves substantial amount of energy compared to unconditional overhearing. With respect to route information, it does not deteriorate the quality of route information by exploiting the spatial and temporal locality of route information dissemination as explained in the introduction. Consider an example in Fig. 3(c), in which nodes X and Y are two neighbors of the communicating nodes A and B. Their communication and overhearing activities are drawn in Fig. 4. When node A receives a RREP from node B, it obtains a new route ($S \rightarrow D$) and stores it in its route cache. Nodes X and Y do not overhear the RREP as shown in the figure but, since there will be a number of data packets transferred from node A to B, they will obtain the route information ($S \rightarrow D$). In this figure, node X overhears the second data packet and node Y overhears the second from the last packet. Fig. 4 also shows when the route becomes stale and gets eliminated from the route cache.

3.2 Rcast Implementation

The Rcast mechanism enables a node to choose no, unconditional, or randomized overhearing when it has a unicast packet to send. Its decision can be specified in the ATIM frame so that it is available to its neighboring nodes during the ATIM window. For practicality,

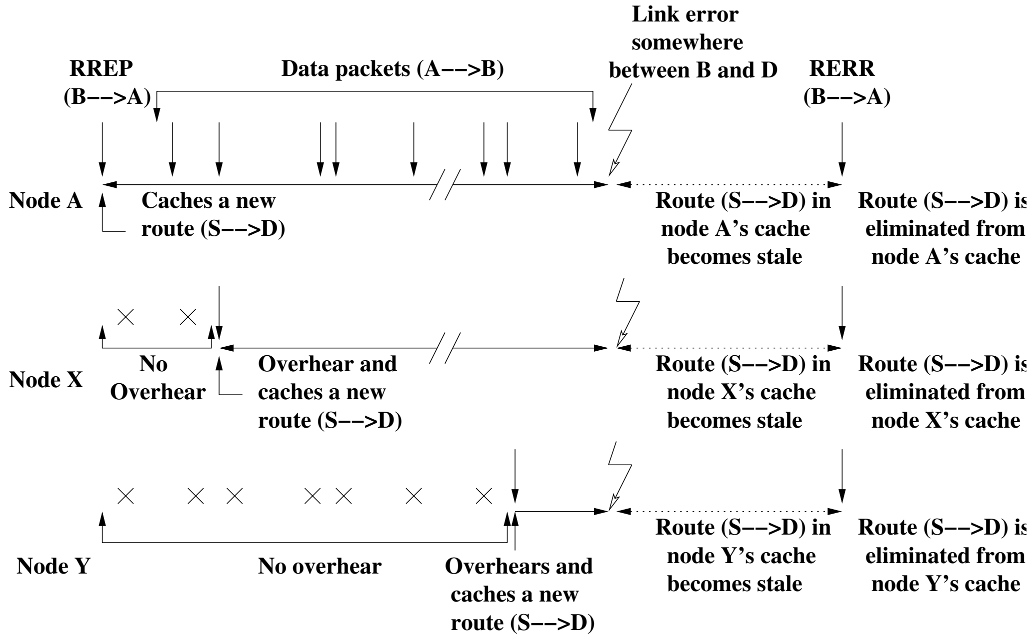


Figure 4: Lifetime of route information at an intermediate node A and neighbor nodes X and Y.

implementation in the context of IEEE 802.11 specification is considered by slightly modifying the ATIM frame format as shown in Fig. 5. An ATIM frame is a management frame type and its subtype ID is 1001_2. The Rcast mechanism utilizes two reserved subtype IDs, 1101_2 and 1111_2, to specify randomized and unconditional overhearing, respectively. An ATIM frame with subtype 1001_2 is recognized as no overhearing, and thus, conforms to the standard.

Consider an example when a node (its MAC address MA) wakes up at the beginning of a beacon interval and receives an ATIM frame. It decides whether or not to receive or overhear the packet based on the destination address (DA) and subtype ID. It would remain awaken if one of the following conditions is satisfied.

1. The node is the intended destination (DA = MA).

2. The node is not the destination but the sender wants unconditional overhearing ($DA \neq MA$ but subtype ID = 1111_2).

3. The node is not the destination, but the sender wants randomized overhearing, and the node randomly decides to overhear the packet ($DA \neq MA$, subtype ID = 1101_2 and decides to overhear).

A key design issue in the Rcast implementation is the mechanism of overhearing when the sender specifies randomized overhearing as in step 3 above. Basically, each node maintains a probability, P_R, determined using the factors listed below and probabilistically makes the overhearing decision based on P_R. In other words, if a randomly generated number is $> P_R$, then a node decides to overhear.

- *Sender ID*: The main objective of Rcast is to minimize redundant overhearing as much as possible. Since a node usually repeats the same route information in consecutive packets, a neighbor can easily identify the potential redundancy based on the sender ID. For instance, when a node receives an ATIM frame with subtype 1101_2, it determines to overhear it if the sender has not been heard or overheard for a while. The former condition means that the traffic from the sender happens rarely or the packet is for a new traffic. The latter condition holds when the node skips too many packets from the sender.

- *Mobility*: When node mobility is high, link errors occur frequently and route information stored in the route cache becomes stale. Therefore, it is recommended to overhear more conservatively in this case. Each node is not knowledgeable about mobility of every other node, but it can estimate its own mobility based on the connectivity changes with its neighbors.

- *Remaining battery energy*: This is one of the most obvious criteria that helps extend the network lifetime: Less overhearing if remaining battery energy is low. However, it is necessary to consider other nodes' remaining battery energy in order to make a better balance.

- *Number of neighbors*: When a node has a large number of neighbors, it is possible that one of them offers a routing path to the node when it asks for it by sending a RREQ. Therefore, the overhearing decision is related inversely to the number of neighbors.

Overhearing decision can be made based on the above four criteria, but in this chapter, we adopt a simple scheme using only the number of neighbors (P_R = 1 / number of neighbors) to show the potential benefit of Rcast. In other words, if a node has five neighbors in its radio transmission range, it overhears randomly with the probability P_R of 0.2.

3.3 Rcast with DSR

As described in Section 2.1, DSR employs three control packets, RREQ, RREP and RERR, in addition to data packets. RREQ is a broadcast and RREP, RERR and data are unicast packets. For each of these unicast packets, DSR uses the following overhearing mechanism.

- *Randomized overhearing for RREP packets*: A RREP includes the discovered route and is sent from the destination to the originator of the corresponding RREQ packet. For example, in Fig. 3(c), node D sends a RREP to node S. Intermediate nodes as well as node D will Rcast this message to allow randomized overhearing. Unconditional overhearing of RREP is not a good idea because DSR generates a large number of RREP packets as discussed in Section 2.1.

- *Randomized overhearing for data packets*: In DSR, every data packet includes the entire route from the source to the destination. Each intermediate node (e.g., nodes

[3]Note that "PwrMgt" in FC indicates the power management mode, either AM or PS, in which the sender of the frame will stay after the current communication is successfully completed.

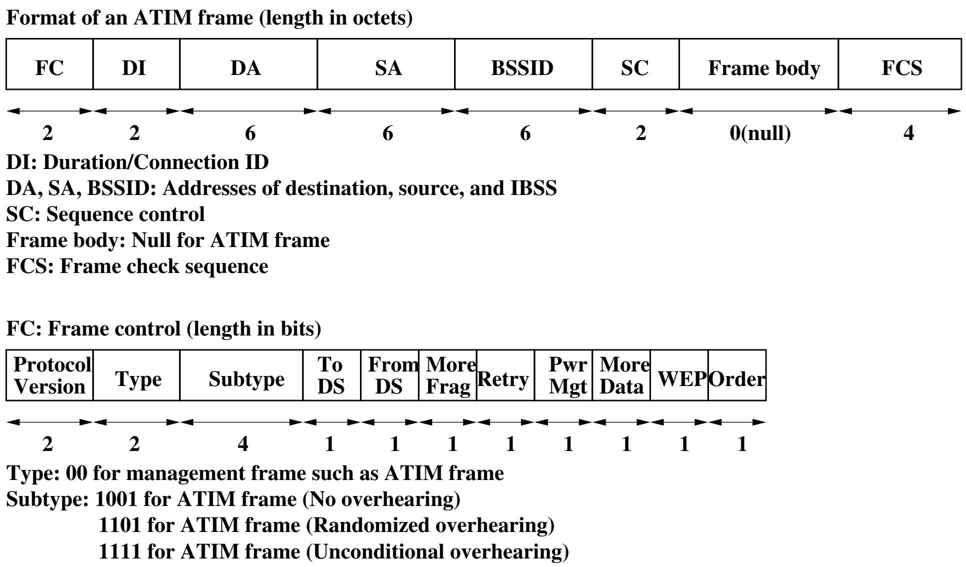


Figure 5: Format of ATIM frame implementing the Rcast mechanism (IBSS: Independence Basic Service Set, DS: Distribution System, and WEP: Wired Equivalent Privacy)[3].

A, B, and C in Fig. 3(c)) as well as the source node (e.g., node S in Fig. 3(c)) will demand randomized overhearing for these packets so that neighboring nodes (e.g., nodes X and Y in Fig. 3(c)) can overhear them randomly.

- *Unconditional overhearing for RERR packets*: When a broken link is detected, an upstream node (e.g., node B in Fig. 3(c)) transmits a RERR to the source. Nodes will overhear this message unconditionally because the stale route information must be invalidated as soon as possible from nodes' route caches.

Note that a broadcast packet such as RREQ can also be Rcasted to allow randomized receiving as mentioned in the introduction. This is to avoid redundant rebroadcasts of the same packet in dense mobile networks. In this case, the overhearing decision must be made conservatively to make sure that the broadcast packet such as RREQ is propagated correctly until it reaches the final destination. Note also that the randomization approach described above can avoid the occurrence of preferential attachment, discussed in Section 2.1, and lead to a more balanced network with respect to packet forwarding responsibility and energy consumption. The overall Rcast algorithm is summarized in Figure 6.

4 Performance Evaluation

4.1 Simulation Testbed

The performance benefits of employing the Rcast scheme are evaluated using the ns-2 network simulator [8], which simulates node mobility, a realistic physical layer, radio network interfaces, and the DCF protocol. Our evaluation is based on the simulation of 100 mobile nodes located in an area of 1500 $\times$ 300 m^2. The radio transmission range is assumed to be

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Notations:
MA, DA: a node's MAC address, and a destination address of packet, respectively.
ID: a subtype of ATIM frame.
| g |: a number of neighbor nodes.

(A) When a node receives an ATIM frame,
    if (DA == MA)      /* the node is the intended destination */
        wake up;
    else {
        if (ID == 1111_2)      /* unconditional overhearing */
            wake up;
        else if (ID == 1101_2) {      /* randomized overhearing */
            P_R = 1 / | g |;      /* overhearing probability */
            r = rand(0, 1);      /* generate a random number between 0 to 1 */
            if (r ≤ P_R)
                wake up;
            else
                sleep;
        }
        else
            sleep;
    }
(B) When a node receives an one of unicast packets (pkt),
    switch (pkt) {
        case RREP: randomized overhearing;
        case DATA: randomized overhearing;
        case RERR: unconditional overhearing;
    }
```

Figure 6: The pseudo code of the Rcast algorithm.

250 m and the *two-ray ground propagation channel* is assumed with a data rate of 2 Mbps. The data traffic simulated is *constant bit rate* (CBR) traffic. 20 CBR sources generate 0.2 to 2.0 256-byte data packets every second (R_{pkt}). *Random waypoint mobility model* [5] is used in our experiments with a maximum node speed of 20 m/s and a pause time (T_{pause}) of 0 to 1125 seconds. With this approach, a node travels towards a randomly selected destination in the network. After the node arrives at the destination, it pauses for the predetermined period of time and travels towards another randomly selected destination. Simulation time is 1125 seconds and each simulation scenario is repeated ten times to obtain steady-state performance metrics.

In our simulation, we use 250ms and 50ms for the size of beacon interval and ATIM window, respectively, as suggested in [26]. We assume that any data packet, which is successfully delivered during the data transmission period, has been successfully announced (and acknowledged) during the proceeding ATIM window. When the traffic is light, this assumption usually holds. When traffic becomes heavier, nodes fail to deliver ATIM frames and would not attempt to transmit packets during the data transmission period. Therefore, the actual performance would be better than the one reported in this chapter.

We compare three different schemes: 802.11, ODPM, and RCAST. 802.11 is unmodified IEEE 802.11 without PSM. As discussed in Section 2.2, ODPM [9] is one of the most

Table 1: Protocol behavior of three schemes.

Scheme	Behavior	Expected Performance
802.11	Does not incorporate PSM and nodes are always awake. Thus, packets are transmitted immediately whenever they are ready.	Best PDR and delay, but consumes the most energy.
ODPM	Nodes remain in the AM mode for a pre-determined period of time when they receive a RREP or a data packet or they are source or destination nodes.	Less packet delay than Rcast because some packets are transmitted immediately. Higher energy cost than Rcast because some nodes remain in the AM mode.
Rcast	All nodes operate in the PS mode consistently and overhearing is controlled. Packets are deferred until the next beacon interval.	Less energy and better energy balance than ODPM.

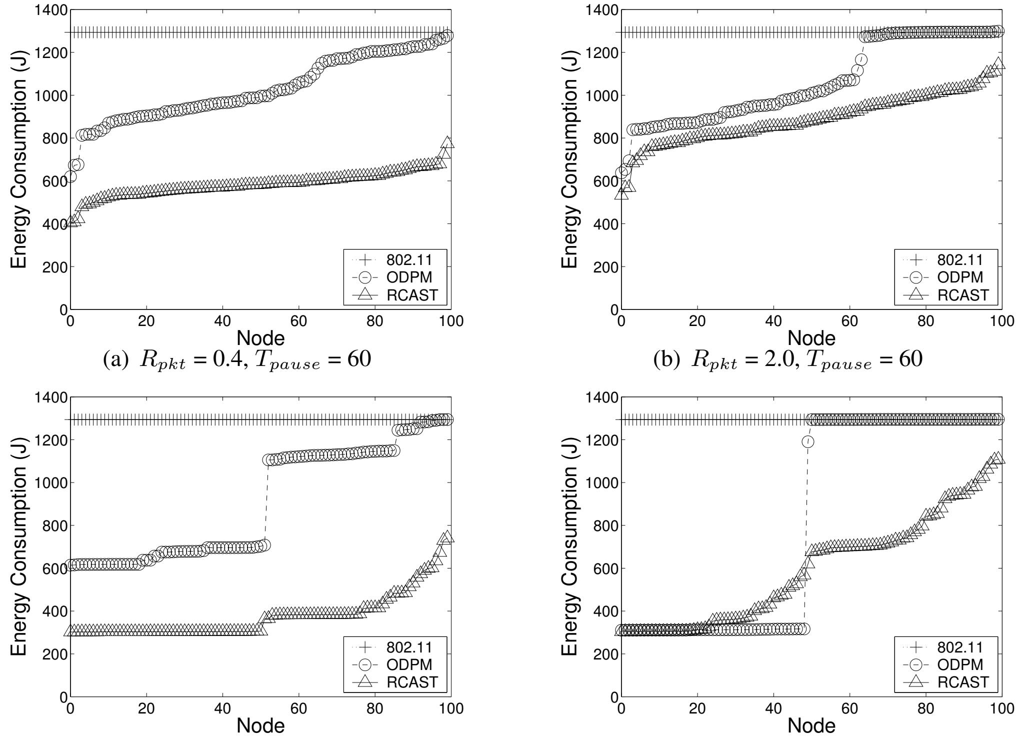
competitive schemes developed for multihop networks, employing on-demand routing algorithms. For ODPM, a node remains in AM for 5 seconds if it receives a RREP. It remains in AM for 2 seconds if it receives a data packet or it is a source or a destination nodes. These values are suggested in the original paper [9]. RCAST uses no/unconditional/randomized overhearing depending on the packet type as explained in the previous Section. Table 1 compares protocol behaviors of the three schemes with their expected performance.

4.2 Performance Metrics

Performance metrics we have used in our experiments are energy consumption, packet delivery ratio (PDR), and packet delay. Energy consumption is measured at the radio layer during simulation based on the specification of IEEE 802.11-compliant WaveLAN-II [1] from Lucent. The power consumption varies from 0.045 W (9mA $\times$ 5 Volts) in a low-power sleep state to 1.15 to 1.50 W (230 to 300mA $\times$ 5 Volts) in idle listening, receiving or transmitting states. In our experiment, we assume nodes consume 1.15W during AM and 0.045W during the low-power sleeping mode. The instantaneous power is multiplied by the time delay to obtain energy consumption. In order to examine the performance tradeoffs, a combined metric has been used in this chapter: Energy consumption to successfully deliver a bit or *energy per bit* (EPB). In addition, energy balance is another important performance measure. We compare the variance of energy consumption of different nodes.

4.3 Simulation Results

Fig. 7 shows the energy consumption of all 100 nodes drawn in an increasing order. Figs. 7(a) and 7(b) use 60 seconds of pause time, while Figs. 7(c) and 5(d) use 1125 seconds (static scenario). Figs. 7(a) and 7(c) simulate low-traffic condition (0.4 packets/second) and Figs. 7(b) and 7(d) simulate higher-traffic scenario (2.0 packets/second). In all the figures, 802.11 consumes the maximum energy and it is the same for all nodes since they are awaken during the entire period of simulation time (1.15W $\times$ 1125 seconds = 1293.75 Joules). RCAST performs much better than ODPM. More importantly, RCAST outperforms ODPM with respect to energy balance, which becomes more significant in a static scenario as shown in Figs. 5(c) and (d). In ODPM, with a packet rate of 2.0 packets/second, the source and destination nodes continue to be awaken (in AM) during the entire 1125 seconds because the inter-packet interval (0.5 second) is smaller than the predefined timeout

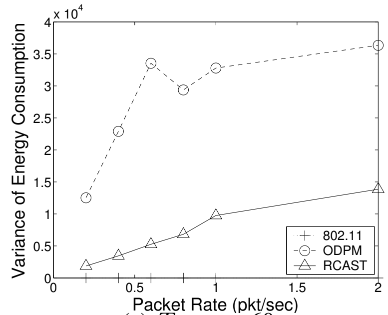


(a) R_{pkt} = 0.4, T_{pause} = 60
(b) R_{pkt} = 2.0, T_{pause} = 60
(c) R_{pkt} = 0.4, T_{pause} = 1125
(d) R_{pkt} = 2.0, T_{pause} = 1125

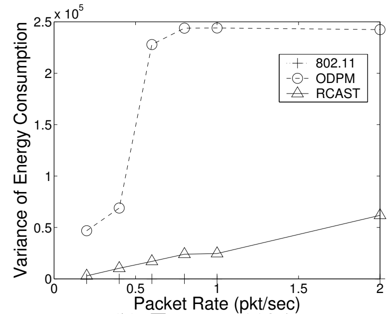
Figure 7: Energy consumption comparison at each node.

values (2.0 seconds). This is also true for all intermediate nodes between the sources and the destinations. Other nodes would not be bothered and wake up only during the ATIM windows consuming less energy (1.15W $\times$ 225 seconds + 0.045W $\times$ 900 seconds = 299.25 Joules) as shown in Fig. 7(d). When packet rate is 0.4 packets/second, the inter-packet interval (2.5 seconds) is longer than the timeout interval, and thus, the energy balance improves but still much worse than RCAST as in Fig. 7(c). It becomes clear in Fig. 8, which shows the energy balance in terms of variance of energy consumption between nodes. 802.11 shows no variance simply because all the nodes consume the same (maximum) amount of energy. With respect to ODPM, RCAST improves energy balance by 243% to 400%, and this is consistently true regardless of the traffic intensity and mobility. Thus, ODPM might be acceptable in mobile and low-traffic scenarios, but RCAST looks more promising in every possible scenario, especially under low mobility or high traffic scenario.

Fig. 9 shows the total energy consumption, PDR and EPB for the three different schemes as a traffic of packet injection rate (0.2 to 2.0 packets/second). Again, 802.11 consumes the largest amount of energy and RCAST performs better than ODPM by 28% to 75% as shown in Fig. 9(a). The performance gap increases between 37% to 131% under a static scenario as depicted in Fig. 9(d). Figs. 9(b) and 9(e) show that all three schemes deliver more than 90% of packets successfully under the traffic condition simulated. EPB, which is a combined metric of PDR and energy consumption, is drawn in Figs. 9(c) and 9(f). RCAST requires as much as 75% less energy than ODPM to successfully deliver a bit. 802.11 suffers even though it shows the best PDR because of its high energy cost.

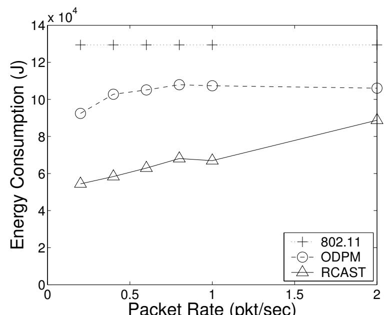


(a) $T_{pause} = 60$

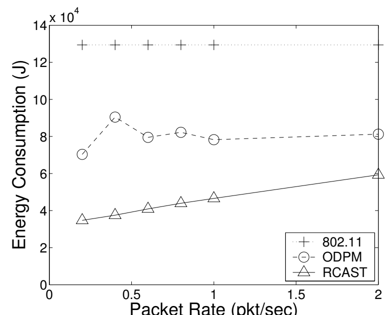


(b) $T_{pause} = 1125$

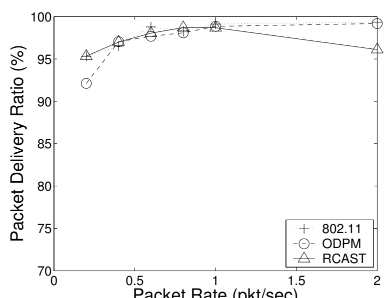
Figure 8: Comparison of variance of energy consumption.



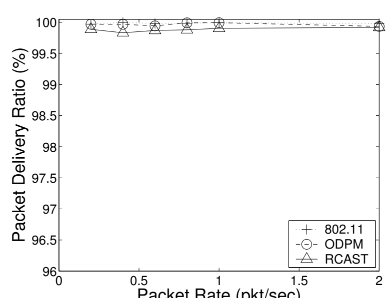
(a) $T_{pause} = 60$



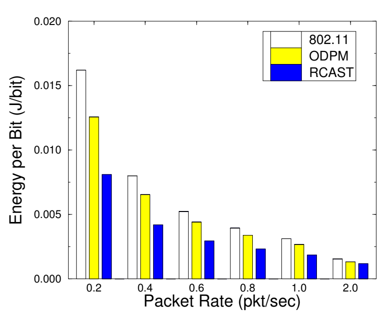
(b) $T_{pause} = 1125$



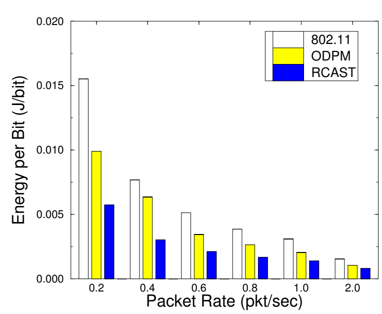
(c) $T_{pause} = 60$



(d) $T_{pause} = 1125$



(e) $T_{pause} = 60$



(f) $T_{pause} = 1125$

Figure 9: Comparison of total energy consumption,packet delivery ratio,and energy per bit.

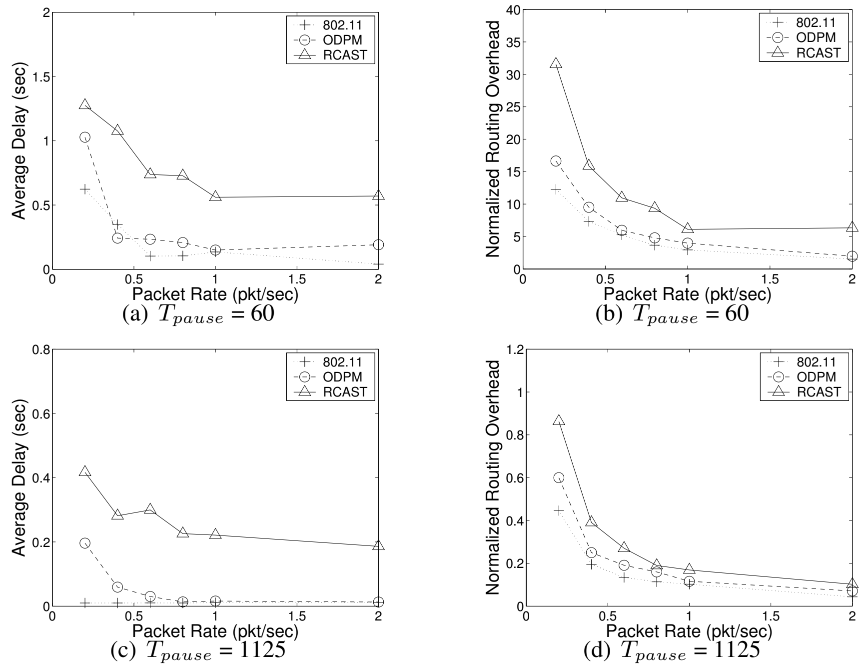


Figure 10: Performance comparison in terms of average delay, and normalized routing overhead.

Fig. 10 shows the average packet delay and normalized routing overhead. As shown in Figs. 10(a) and 10(c), the packet delay is the smallest with 802.11 and ODPM. This is because all (802.11) or some (ODPM) data packets are transmitted immediately without waiting for the next beacon interval as discussed in Section 4.1. In RCAST, each packet must wait, on an average, half of a beacon interval (125 msec) for each hop, resulting in an extended delay compared to 802.11 and ODPM. On the other hand, routing efficiency is evaluated using the normalized routing overhead, measured in terms of the number of routing-related control packets per a successfully delivered data packet. Comparing the static (Fig. 10(d)) and mobile (Fig. 10(b)) scenarios, we observe that the overheads are significantly different. Since, in a mobile scenario, there would be more link errors and more route discoveries, it is expected that the routing overhead becomes significantly large. In each scenario, it is observed that the overhead is the smallest with 802.11 and the other protocols behave similarly. In other words, RCAST performs at par with ODPM even with limited overhearing.

5 Conclusions

IEEE 802.11 is the most widely used wireless LAN standard specifying the physical and MAC layer protocols. While there has been active study on multihop networks with respect to many aspects including energy conservation, there is little effort about how to integrate the well-known IEEE 802.11 PSM with a multihop routing protocol such as DSR. This study addresses this important problem and suggests an efficient solution based on Random-

Cast (Rcast). The key idea behind the Rcast development is that unconditional overhearing, which is taken for granted without PSM, is not freely available with PSM. This is because packet advertisement is announced independently with respect to actual packet transmission, and thus, nodes which are not interested in receiving a particular packet can sleep during the actual transmission time to conserve energy. Therefore, nodes have an option whether to overhear or not a packet advertisement, and this decision must be made considering the tradeoffs between energy efficiency and routing efficiency. Routing efficiency comes into picture because overhearing is an important tool to gather route information in DSR.

This chapter identifies four factors that must be considered for the overhearing decision. These are sender ID, mobility, remaining battery energy, and number of neighbors. We implemented the Rcast scheme using only the last factor (number of neighbors), and compared it with four other schemes in terms of PDR, packet delay, energy consumption, and routing overhead through simulation. Our results indicate that Rcast significantly outperforms ODPM (as much as 28% to 131% less energy), which is the most competitive scheme developed for multihop networks employing on-demand routing algorithms, without significantly deteriorating the general network performance such as PDR. Rcast also improves energy balance by 243% to 400% in terms of variance in battery energy consumption. The performance results indicate that the proposed scheme is quite adaptive for energy-efficient communication in MANETs. In particular, applications without stringent timing constraints can benefit from the Rcast scheme in terms of power conservation.

Rcast opens many interesting directions of research to pursue. First, we plan to investigate the effect of other three factors (sender ID, mobility, and remaining battery energy) for making the overhearing decision. Since these factors increase the corresponding overheads, we also need to assess their tradeoffs. In particular, sender ID is the most compelling idea and can be implemented easily with a simple hashing function. Remaining battery energy will play an important factor if energy balance is critically important. We plan to explore the use of Rcast for broadcast messages and to incorporate the concept with other routing protocols.

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