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An architecture for power-saving communications in a wireless mobile ad hoc network based on location information

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Abstract

A *mobile ad hoc network (MANET)* is one consisting of a set of mobile hosts which can operate independently without infrastructure base stations. Power saving is a critical issue for MANET since most mobile hosts will be operated by battery power. In this paper, we propose an architecture for power-saving communications in an IEEE 802.11-based MANETs. Our solutions are derived by exploiting the location information of mobile hosts to achieve the goal of energy conservation. The architecture addresses the power-saving issue on several protocol layers, including network, medium access control (MAC), and physical layers. In comparison, existing protocols only exploit location information in limited layers. Similar to cellular networks, our approach is based on partitioning the network area into squares/hexagons called *grids*, thus leading to powerful energy and mobility management capabilities. A superframe architecture is proposed on the MAC part to support inter-grid and intra-grid communications. Simulation results are presented to demonstrate the strength of the proposed protocols.

Keywords: Energy conservation; Location awareness; Mobile ad hoc network (MANET); Mobile computing; Power saving; Wireless network

1. Introduction

The *mobile ad hoc network (MANET)* has attracted a lot of attention recently. This paper investigates the design of power-conserving communication protocols for MANETs. A protocol's behavior does have significant impact on power consumption [1,3,18]. So a host should tune its wireless interface card to the doze mode whenever possible, under the condition that this will not hurt its own and the network's performance. In this paper, we propose a communication architecture that addresses the power-saving issue covering several protocol layers, including network, medium access control (MAC), and physical layers. The proposed protocols are *location-aware*, in the sense that we try to exploit the physical location information of mobile hosts to achieve the goal of energy-conserving communications. In comparison, existing protocols only exploit location information in limited layers (e.g. power control is covered in [9,16], power mode management in [2,7,18], power-aware MAC in [1,10,17], and power-aware routing in [11,13]). Table 1 compares existing schemes and ours based on the above categorization.

The proposed architecture is based on the availability of location information and the partitioning of the network area into squares/hexagons, called *grids*. Routing is conducted in a grid-by-grid manner. To choose routing paths, we adopt *collective energy*, which is defined to be sum of energies of all hosts within a grid, as the metric. To save hosts' energies, a power management mechanism is proposed to reduce the number of awake hosts in a grid without hurting the connectivity of the network. To reduce unnecessary collisions (and thus save energies), we separate inter-grid from intra-grid communications into two parts under a superframe structure. The superframe structure is similar to that of IEEE 802.11. Specifically, intra-grid and inter-grid communications are supported by PCF and DCF mechanisms of IEEE 802.11, respectively. Frequency reuse patterns are proposed to increase frequency efficiency as well as to resolve the interference problem in intra-grid communications. Physical-layer power control can be easily conducted under the proposed architecture because the maximum communication distances for intra-grid

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Table 1
Categorization of protocols

Protocol	Routing	Power mode Mgt	MAC	Power control
[11,13]	PA			
[5,6,8]	LA			
[12,19]	LA + PA			
[2,7,14]		PA		
[18]		LA + PA		
[1,10]		PA	PA	
[17]			PA	PA
[4]			LA + PA	LA + PA
[9,16]				LA + PA
[15]	LA + PA			LA + PA
Ours	LA + PA	LA + PA	LA + PA	LA + PA

PA, power-aware; LA, location-aware.

and inter-grid transmissions are predefined and locations of hosts are available. Simulation results are presented to demonstrate the efficiency of the proposed protocols. The proposed architecture is presented in Section 2. Section 3 contains our experimental results, and Section 4 concludes this paper.

2. Power-saving communication architecture

Our goal is to propose an integrated architecture that is both power-aware and location-aware. Each host is assumed to be equipped with a GPS receiver. This paper extends the ideas in [6,18] and shows how location information can be utilized for a full-scale power-saving communication architecture that covers layers 1, 2, and 3. Our work distinguishes from earlier works in the following ways:

- We address the important MAC part that is missing in the earlier works [6,18]. A superframe structure similar to that of IEEE 802.11 is proposed to accommodate intra-grid and inter-grid communications. The framework not only reduces unnecessary communication contentions among mobile hosts, but also provides a clear way to conduct mobility management and power management.
- On top of the MAC part, the architecture also contains a regular channel assignment pattern to separate the intra-grid communications among different grids. This not only improves the channel reuse factor of physical channels, but also resolves the inter-grid interference problem during intra-grid communication periods and thus saves more energy that otherwise need to be paid for retransmissions.
- Since intra-grid and inter-grid communications are separated, transmission power control on the physical layer can be easily done under our framework.
- While routing is also conducted in a grid-by-grid manner similar to that in [6,18], the collective energies of grids are used as our route selection metric. This can further balance hosts' expenditures in relaying other hosts' packets, and thus lengthen the lifetime of the network.

2.1. Grid formation and channel assignment

The geographic area of the MANET is partitioned into virtual cells called *grids*. Two types of grid systems are considered in this work: *square* and *hexagon* as illustrated in Fig. 1. In both cases, we use d to denote the side length of a grid. We assume that each mobile host is equipped with a GPS receiver, and the system is designed for outdoor use. Since each mobile host knows its current location and how grids are defined, it can easily tell which grid it is currently resident in. In each grid, a leader will be elected based on some energy and location criteria (to be discussed later).

In the MAC part, we will separate communications into two phases: intra-grid phase and inter-grid phase. The inter-grid phase is for all leaders to communicate with each other, and a common channel will be used for their communications. The intra-grid phase is for all non-leader hosts to communicate with their leaders. During this period, each grid will be assigned a separate channel for its own communications. Neighboring grids should be assigned different channels to avoid the interference problem. Overall, the network will have a common *inter-grid channel*, and each grid will have its own *intra-grid channel*.

We suggest that the channel assignment during the intra-grid phase be done as shown in Fig. 1, where the number in each grid represents the channel to be used by that grid.

In the square-grid case, totally four channels are needed, while in the hexagon-grid case, only three channels are needed. In either case, the channels of neighboring grids form a pattern, called a *cluster*, which will appear repeatedly in a regular way. Taking the square-grid system for example, four neighboring grids form a cluster. If we number grids by (i,j) based on their xy-coordinates, all grids with the equal value of $((i+j) \bmod 4)$ will be assigned the same channel. Note that IEEE 802.11b DSSS typically offers 11–13 channels, among which 3–4 channels are interference-free. This would fit well into the above model.

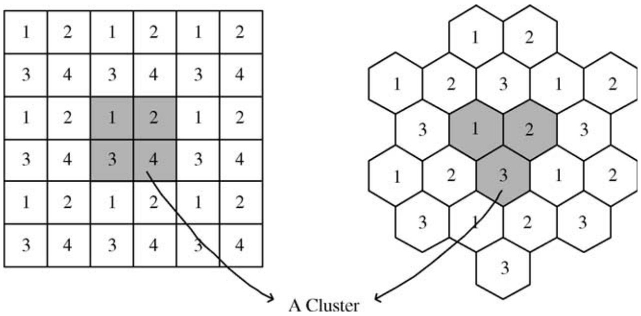

Fig. 1. The square-grid and hexagon-grid systems. The number in each grid indicates the channel assigned to it during the intra-grid communication phase.

2.2. Medium access control (MAC)

In our design, we separate intra- from inter-grid communications. The former is supported by the point coordination function (PCF) of IEEE 802.11, while the latter supported by the distributed coordination function (DCF) of IEEE 802.11. Also, since only hosts that are leaders need to get involved in the inter-grid communication phases, non-leaders can switch to a low-power mode to save energy. Using PCF can also support certain degrees of QoS.

The time axis is divided evenly into a sequence of *superframes*, each of length T_{super}, where T_{super} is a global parameter known by all hosts participating in the network. Each superframe is divided into four phases: *leader phase*, *election/registration phase, intra-grid* phase, and *inter-grid phase*, as shown in Fig. 2. In the first three phases, only intra-grid communications will appear, so the intra-grid channels should be used. The last phase is for inter-grid communications, so the inter-grid channel should be used. The first two phases, called 'controlling part', are mainly for managing and maintaining a grid. The important mobility and power management functions will be conducted during this part. The leader phase is for leaders to send important broadcast information. In this phase, all hosts must be awake and only leaders have right to access their (intra-grid) channels. If a leader exists in a grid, the next phase in the grid will become a registration phase, which is for the leader to maintain the memberships of non-leaders in the same grid. If no leader exists, the next phase will become a leader election phase, which is for hosts to compete to become a leader. The detail packet exchange will be further elaborated in later subsections.

The next two phases, called 'data part', are mainly for sending higher-layer payloads. In the intra-grid phase, the leader polls its slaves in a round-robin manner. The polling list may contain slaves with buffered packets in the leader's side and those who are not in the sleep mode. The packet exchange is supported by the PCF of IEEE 802.11. Specifically, POLLs are sent to slaves one by one. Data payloads can be combined with POLLs. On being polled, a slave can return a data packet targeted at the leader or another slave in the same grid. The PIFS (PCF inter-frame spacing) should be used to separated frames in this phase. In the inter-grid phase, only leaders can send/receive packets. Its main purpose is to route packets to their destinations in a grid-by-grid manner. Some (layer-3) control packets containing routing information can also be delivered in this phase. This phase is supported by the DCF of IEEE 802.11, so hosts should contend to send packets based on CSMA/CA using RTS/CTS dialogues. The DIFS (DCF inter-frame spacing) should be used to separated frames in this phase.

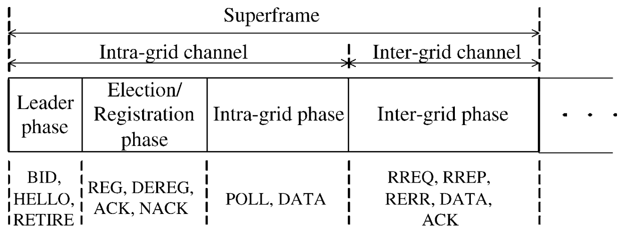

Fig. 2. The structure of a superframe.

Note that superframes need to be synchronized among all grids. This can be supported by GPS. Superframes need to be synchronized (but not perfectly synchronized) in the long run, and this should be achievable by GPS. Also, the clocks of hosts within the *same* grid need to be synchronized so that hosts will not miss the important information transmitted during the leader phase. Local clock synchronization among hosts in the same grid should be easy.

2.3. Mobility management

Mobility management is essential in our architecture to maintain the correct operation of grids. Packets are sent during the controlling part for this purpose. A leader election protocol is run in each grid to determine its leader. Once a leader is elected, the leader will maintain the memberships within the grid. Leaders are elected based on two concerns: energy and location. For each host i, its remaining energy at time t is denoted by c_i^t, which is a value between 0 and 1, with 1 representing a fully charged battery. We rank a host's energy c_i^t into n levels, such that level j satisfies $(j-1)/n < c_i^t \leq j/n, j = 1, \ldots, n$.

Each leader should periodically broadcast a $HELLO(g, id, T_{next\_super}, Tab_{slaves})$ packet using its intra-grid channel, where g is the grid identity, id is the leader's identity, T_{next_super} is the remaining time that the next superframe is expected to appear, and Tab_{slaves} indicates the registered slaves in the grid. This packet should be sent in the beginning of the leader phase. However, since the time that a *HELLO* packet appears may be delayed by packets in the previous inter-grid phase, the value T_{next_super} is to take the delay into account. This helps synchronize clocks of hosts in the same grid, especially for those newly entering this grid.

If a *HELLO* packet does not appear during the leader phase, the next phase will become a leader election phase. Fig. 3 shows the state transition of our leader election protocol. Whenever a host i finds that it is unaware of any leader in its grid, it should enter the competing state and remain active. It then contends to become a leader by broadcasting a $BID(i, g, loc, c_i^t, T_{bid})$ packet, where g is the grid identity, loc is i' current location, and T_{bid} is a timeout value. When a host j in the same grid, which is also in the competing state, receives i's *BID*, it compares its own condition against that of i's. Three cases may happen: (a) if j's energy is ranked better, it will keep on contending to broadcast its own *BID* packet, in which case host j disagrees

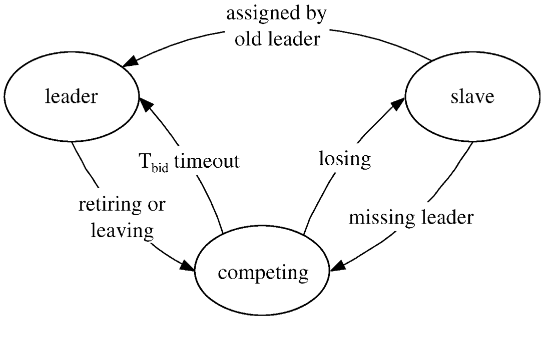

Fig. 3. State transition in our leader election protocol.

host i to become a leader. (b) If i's and j's energy ranks tie, j further compares its current location against i's. If j is closer to the center of the grid than i, it will also keep on contending by broadcasting its own *BID* packet. (c) If both of the above two cases fail, j will simply keep silent, which means that j consents to i's bid as a leader. The loser should then enter the slave state. If i receives any *BID* from other hosts after its *BID,* it also keeps silent and enters the slave state. Host i, on detecting no other *BID* for time interval T_{bid} after its own bid, assumes itself as the leader and enters the leader state by immediately sending a *HELLO* packet. Any host who hears the *HELLO* packet must concede by entering the slave state, even if it has better energy rank or is closer to the center of the grid. This is to reduce the election cost. Note that since more than one host may try to compete as a leader, the *BID* packets should be sent in a contention basis. This can be done following the CSMA/CA mechanism in IEEE 802.11. Also, note that transmission errors may cause a host trying to contend as a leader even if the leader already sent a *HELLO* packet in the leader phase. To tolerate this kind of faults, the leader can immediately reply a *HELLO* after hearing a *BID* packet after a *SIFS* (short inter-frame spacing) interval to discourage the bidder. In the definition of IEEE 802.11, *SISF* is shorter than *PIFS,* which is in turn shorter than *DIFS.* So the *HELLO* packet from the leader will have the highest priority over other possible *BID* packets.

If a leader exists, the second phase will become a registration phase. A slave i should periodically register with its leader in registration phase by sending a $REG(g, i, loc, c_i^t, T_{reg})$ packet, where g is the grid identity, loc is i's current location, c_i^t is i's current energy rank, and T_{reg} is the number of superframes that the registration is expected to be effective. The last parameter means that the registration expires after a time interval $T_{reg} \times T_{super}$, unless the host refreshes its registration by then. A host does not register after timeout will be regarded as leaving the grid and will not be polled in the next intra-grid phase. The leader replies an *ACK* immediately after a *SIFS* interval. The leader should maintain a table to keep track of its local slaves, and the memberships are announced periodically in the *HELLO* packet in the parameter Tab_{slave}. A slave can choose a proper T_{reg} based on its mobility and energy constraint. We recommend that a reasonable value for T_{reg} could fall between 3 and 5. Note that since more than one host may try to register, the *REG* packets should also be sent in a contention basis following the CSMA/CA mechanism in IEEE 802.11.

A host, on newly entering a grid, should wait for the next *HELLO* packet from the corresponding leader, in which case it can reply a *REG* to register. If no *HELLO* is detected after an interval of T_{super}, the host can compete by sending a *BID* (it is likely that this host is the only host in the grid). The procedure is similar to the above bidding procedure. Before a slave i leaves its current grid g, it can send a $DEREG(g, i)$ to deregister from its leader. This can save the leader's effort in polling this slave during the intra-grid phase. However, sending *DEREG* is optional because anyway the registration will expire after T_{reg} as discussed above.

A leader, when leaving its current grid, must inform its slaves by sending a $RETIRE(g, id, Tab_{slaves}, RT)$ packet in replace of *HELLO* during the leader phase, where *RT* is the leader's routing table. In this case, it returns to the competing state. Other slaves, on hearing the *RETIRE,* will enter the competing state. Then the earlier bidding procedure follows. The transmission of *RT* is for the new leader to immediately catch up with the routing job during the inter-grid phase. This interesting 'handover' process helps one leader shifts its job to another easily. An alternative to sending a *RETIRE* is for the old leader to directly assign a slave j as a new leader by sending an $ASSIGN(g, id, Tab_{slaves}, RT, j)$ packet during the leader phase. This saves the contentions and efforts to elect a new leader. This is shown in Fig. 3 by the direct transition from the slave state to the leader state. Note that this is possible due to the fact that the old leader is aware of its slaves' locations and energy ranks from their *REG* packets.

A leader may also become unwilling to serve in the position, either because its location is very close to the boundary of the grid, or because its energy rank is comparatively much worse than its slaves, in which case it can also send a *RETIRE* or an *ASSIGN* packet. However, one exception is that when a leader is the only host in the grid and there are several active routing paths passing it, then it is not allowed to retire.

Finally, we comment that, due to the existence of obstructions, multiple grid leaders may coexist in one grid. If so, these leaders must be unable to hear each other. So they will maintain their own superframes based on their clocks. These leaders will use the same intra-grid channel during the first three phases, and use the same inter-grid channel during the last phase. This may cause some performance degradation during the intra-grid phase. A slave should register with at most one leader at a time, even if it can hear multiple leaders. During the inter-grid phase, all leaders will communicate in a contention basis. So the correctness of our protocol will not be affected.

2.4. Power management and power control

Our design allows power management and power control in each node. In the power mode management part, hosts which serve as leaders must remain active all the time. As to slave hosts, they can always go to a doze mode during the inter-grid phases. A slave can also refuse to participate the intra-grid phases by properly informing its leader. Specifically, this can be done by adding one more field T_{sleep} in the *REG* packet, by which the slave informs its leader that it is going to enter a doze mode in the next T_{sleep} superframes. The leader can either accept or reject the request in its responding *ACK* packet. A dozing host should still wake up periodically to monitor the *HELLO* packet, but it will not be polled during the intra-grid phases. So it may suffer from packet dropping if the leader's buffer overflows. On the other hand, the leader may also indicate in its *HELLO* packets its intention to 'wake up' those dozing hosts that have buffered packets in the leader's side. This information can be included in the Tab_{slaves} field. In this way, a slave can also immediately wake up by reregistering with the leader to cancel its dozing status. Note that a host may be in the sleeping mode while it is entering a new grid. On finding such a situation, it should switch to the active mode immediately to register with the current grid leader or bid as a leader if there is no leader in this grid.

For power control, intra-grid and inter-grid communications should use different power levels. Fig. 4 shows this concept, where transmission distances are denoted by s_1, s_2, h_1, and h_2.

2.5. Network layer

Routing is conducted in two levels: intra-grid and inter-grid. For intra-grid routing, if a packet is targeted at a host resident in the same grid, it can be sent to that host directly during the intra-grid phase. For packets targeted at a different grid, they are always forwarded to the leaders first. Then inter-grid routing will be conducted during the inter-grid phases by leader hosts. We adopt the *on-demand* routing style to establish routing tables on leader hosts. Route selection is conducted with energy concerns. Specifically, we define the *collective energy* of a grid (i,j) at time t to be the sum of all battery energies of the hosts within this grid, i.e. $C_{i,j}^t = \sum_{k\in(i,j)} c_k^t$. We suggest that route discovery and route maintenance can be done following the protocols in [6], so we will not further elaborate. The major difference is that when multiple alternative routes are present in the route discovery procedure, we need to choose one that is more energy-conserving. We propose four route selection strategies:

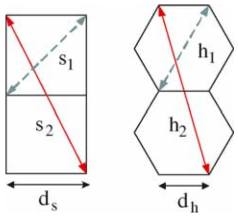

Fig. 4. The maximum transmission power levels for intra-grid and inter-grid communications in square- and hexagon-grid systems ($s_1 = \sqrt{2}d_s$, $s_2 = \sqrt{5}d_s$, $h_1 = 2d_h$, $h_2 = \sqrt{13}d_h$).

- *Shortest-Path, Max-Total (SPMT)*: Among all paths with the minimum hop count, the one with the maximum total collective energy over all grids passed by the path is selected.
- *Shortest-Path, Max–Min (SPMM)*: Similar to SPMT, we first pick all paths with the minimum hop count. For each path, we further identify the grid with the minimum collective energy in the path. We select the path whose minimum energy is maximized.
- *Max-Average-per-Hop (MAH)*: For each path, we calculate the average collective energy of all its grids. Then we divide the average collective energy by the path's length. The one with the maximum value is selected.
- *Max–Min-per-Hop (MMP)*: This is similar to MAH, except that the average collective energy is replaced by the minimum of the collective energies of grids along the path.

These route selection metrics are defined following the rules in [11] as guidelines. Note that the first two strategies always choose the shortest paths. Under our regular square- and hexagon-grid structures, multiple paths may have the same hop count leading to the destination grid. Then one path is selected with energy concerns. The last two strategies do not necessarily choose the shortest paths.

3. Experimental results

3.1. Simulation model

A MANET with 9×9 square/hexagon grids within an area of $1000\ \mathrm{m} \times 1000\ \mathrm{m}$ is simulated. We set hosts' maximum transmission distance to be $s_2 = h_2 = 250$ m. According to Fig. 4, this gives $d_s = 250/\sqrt{5}$, $d_h = 250/\sqrt{13}$, $s_1 = 250\sqrt{2}/\sqrt{5}$, and $h_1 = 250 \times 2/\sqrt{13}$ m. A host has three transmission power levels in both the intra- and inter-grid communications. Specifically, in the square-grid case, a host can transmit in three possible distances of s_1, $(2/3)s_1$, and $(1/3)s_1$ at the intra-grid phase, and s_2, $(2/3)s_2$, and $(1/3)s_2$ at the inter-grid phase. Hosts can choose the most appropriate power levels.

We assume IEEE 802.11b wireless LAN devices data rate of 11 Mbits/s. Unless specified otherwise, each superframe is of length 200 ms, in which the leader phase occupies 1 ms and the leader/registration phase occupies 4 ms. The ratio of the length of an intra-grid phase to that of an inter-grid phase is 1:4. For the intra-grid part, medium access is based on a simple round-robin polling. Only hosts serving as sources/destinations/relays of routes will be polled. Unicast data frames are always protected by control frames (RTS, CTS, and ACK), each approximated by a length of 25 bytes.

As to the routing part, path discovery is conducted in an on-demand manner following the DSR style. The only difference is that paths are selected with different energy metrics, as described in Section 2.5. The flooding of route requests is limited to the rectangle that bounds the source and destination hosts as suggested in [6]. Note that this confined flooding is only done when a route currently under use is found to be broken, in which case the source knows the destination's location right before the breakage event happened. For a destination with which the source does not communicate recently, network-wide flooding among all leaders is taken. Three parameters are tunable in our simulations.

- *Host density*: We may vary the total number of hosts in the network. Since the network area is fixed, this number reflects the host density.
- *Traffic load*: To reflect the load, routes are generated into the network with a controllable rate from 0.1 to 10 routes/s. Each route has a pair of randomly selected source and destination and has a fixed lifetime of 10 s. Packets are generated to each route at a constant rate of 200 packets/s, each of size 1500 bytes.
- *Roaming model*: Each host moves in a random way-point-like model as follows. In every 30-seconds interval, the host randomly selects a destination, and moves toward that destination with a constant speed between 2 and 10 m/s. If it arrives at the destination before 30 seconds, it stops there until the next 30-seconds interval starts. This behavior repeats every 30 seconds.

In the beginning, each host has a total energy of 40,000 mJ. The power consumption model of wireless LAN cards on transmission, reception, monitoring, and doze are 280, 180, 70, and 10 mW, respectively. Note that the 'monitoring' mode reflects the power consumption when a host (in the active mode) is receiving a packet that is not destined to itself. A host is allowed to send a RETIRE packet when it detects that one of its members has an energy level higher than its own by a leader-retiring threshold. This threshold is a certain percentage of the initial energy (i.e. 40,000 mJ). Unless specified otherwise, we adopt 20%.

3.2. Observed results

We denote our protocols by *GRID-S* and *GRID-H* for the square- and hexagon-grid systems, respectively. Based on which routing metric is used, each protocol has four versions: SPMT, SPMM, MAH, and MMP. We mainly compare our result to the *always-active (AA)* protocol, where hosts do not conduct power mode management (and thus never go to sleep). Two versions of AA are implemented, one called *AA-C*, where transmission power levels always remain as a constant, and one called *AA-V*, where transmission power levels could be variable. AA-C always uses the largest possible power level for transmission, while AA-V always tunes to the minimum possible power level to transmit (such as that in PAMAS [10][1]). (A) *Host Survival Ratio*. First, we evaluate the *host survival ratio*, which is defined to be the number of hosts with non-zero energy divided by the total number of hosts after the network is operating for a certain amount of time. The results are shown in Fig. 5. We vary the number of hosts and roaming speed. Benefited from our power mode management mechanism, GRID-H can greatly improve the lifetime of the network compared to AA. A denser network can sustain for longer time compared to a sparser network for GRID-H, which is reasonable because in each grid, we only require its grid leader to remain active and the rest of the hosts can go to sleep. On the contrary, the AA schemes do not enjoy this nice property. A higher roaming speed will somehow degrade the host survival ratio because there is higher maintenance cost for leader elections. Among the four route selection strategies that we proposed, the MMP strategy generally has the best performance when the network is denser and host mobility is higher (for sparser and less mobile networks, the effect of routing strategies is not distinguishable). The other three schemes perform about the same. However, the gap is not significant. Thus, we conclude that power mode management can contribute more in terms of energy conservation than routing strategies. In the rest of the experiments, we will discuss only MMP, and omit our simulation results for the other routing strategies. (B) *Leader-Retiring Threshold*. This threshold indicates when a leader is allowed to retire and 'handoff' its routing table to the next leader. We test several thresholds, which are represented by the portion of a host's initial energy. The result is shown in Fig. 6, where ratios of 5, 10, 15, 20, 25, 30, 35, and 40% are tested. For example, a ratio of 10% means that a leader is allowed to retire if its remaining energy is less than one of its members by 4000 mJ. As can be seen, the best ratio is around 20%. A ratio that is too small has the disadvantage of too many reelections. A ratio that is too large is also not preferred because of unfairness for those hosts serving as leaders. (C) *Effect of Superframe Length*. In Fig. 7, we vary the length of superframes to observe its effect. We evaluate the *power-saving ratio*, which is defined to be $1 - ($(energy consumption per second of GRID-H(MMP))/(energy consumption per second of AA)). With shorter superframes, sleeping slaves need to wake up more frequently to listen to and register with leaders, so the amount of saving is lower. Longer superframes do save more energy, but the amount of saving is becoming more insignificant as we keep on

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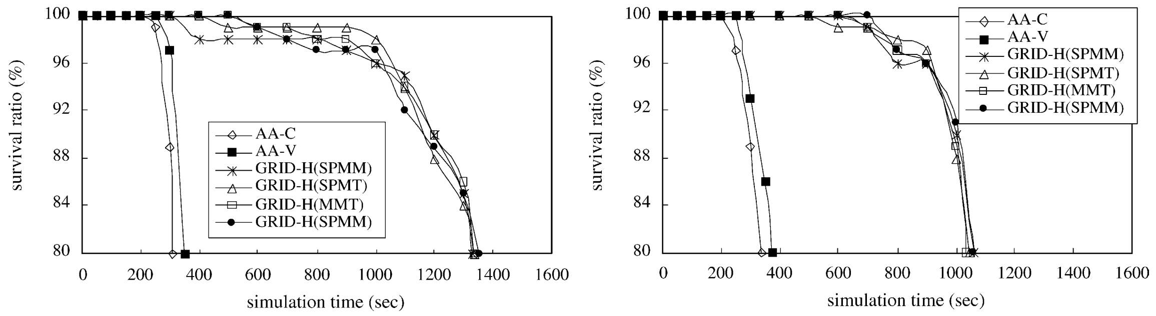
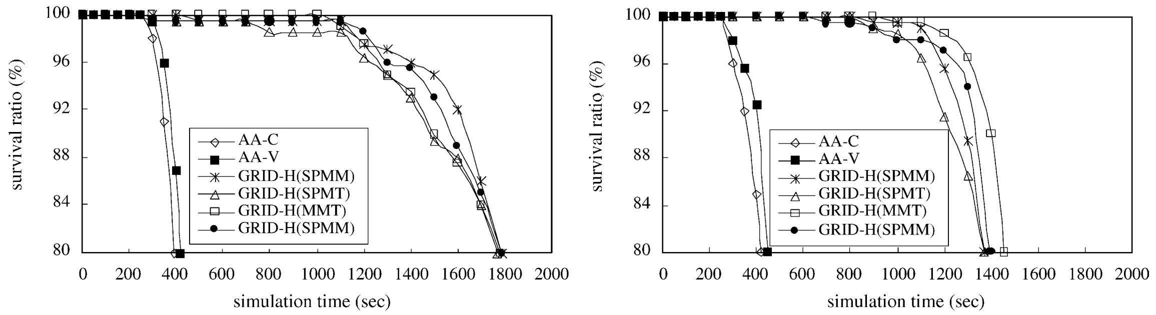
[1] However, for simplicity, the extra control channel and the related costs incurred by PAMAS are ignored in the measurement.



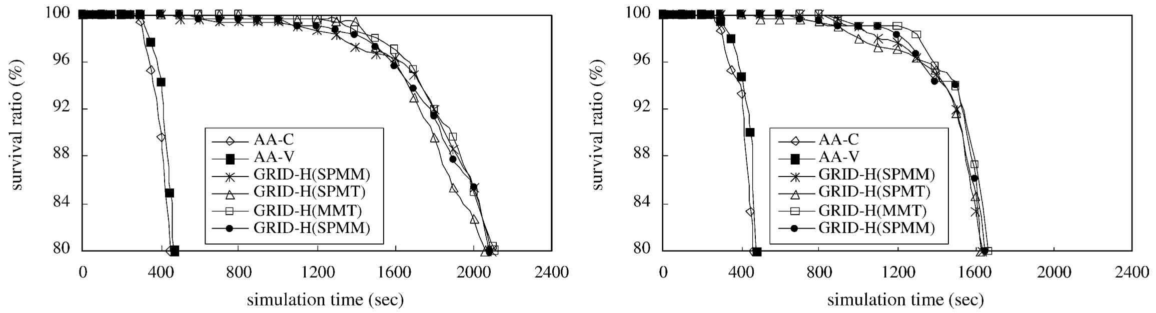
(a) 100 hosts, speed = 2m/sec

(b) 100 hosts, speed = 10m/sec



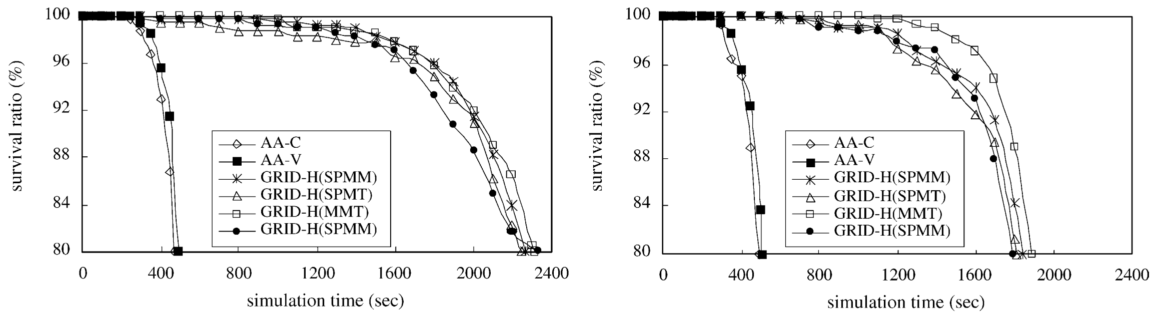
(c) 200 hosts, speed = 2m/sec

(d) 200 hosts, speed = 10m/sec



(e) 300 hosts, speed = 2m/sec

(f) 300 hosts, speed = 10m/sec



(g) 400 hosts, speed = 2m/sec

(h) 400 hosts, speed = 10m/sec

Fig. 5. Host survival ratio vs. simulation time (route generation rate = 1 route/s, inter-grid phase = 75%).

increasing the superframe length. The trend is similar for different host densities, which is reasonable. However, a longer superframe incurs longer response time for intra-grid communications, so its length should not be arbitrarily large. Considering the curves in the figure, a proper superframe length would be around 200–300 ms.

(D) *Power Consumption and Throughput*. Next, we evaluate two factors: power consumption per second and network throughput. We vary the traffic load (by varying the route generation rate) to observe these two factors.

Again, to exclude extreme cases, we only measure these factors up to the time when 20% of hosts in the network run

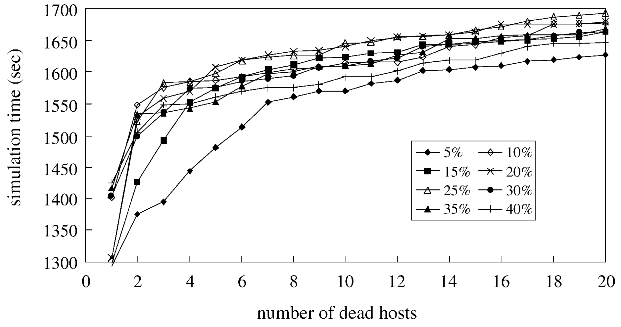


Fig. 6. Simulation time vs. number of dead hosts (route generation rate = 0.1 route/s, inter-grid phase = 75%, number of hosts = 300, speed = 10 m/s).

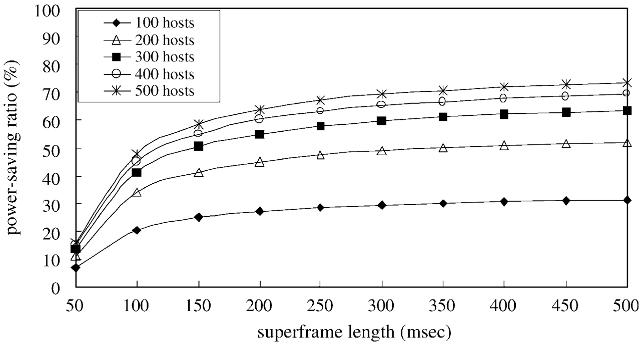


Fig. 7. Power-saving ratio vs. superframe length (route generation rate = 1 route/s, number of hosts = 300, inter-grid phase = 75%, speed = 10 m/s).

out of energy. The results are in Fig. 8. It is clear that GRID-H can significantly reduce the energy consumption compared to AA schemes. Interestingly, the network performance is not degraded by the reduction of radioactivity. The average number of packets being processed (on layer 2) per second is larger than that of the AA protocol. We believe that this is contributed by the reduction in contentions with our grid structure and the support of polling mechanisms in the intra-grid phases. Note that if we multiply this factor by the network lifetime (which is not shown in this figure), the benefit will be even more significant.

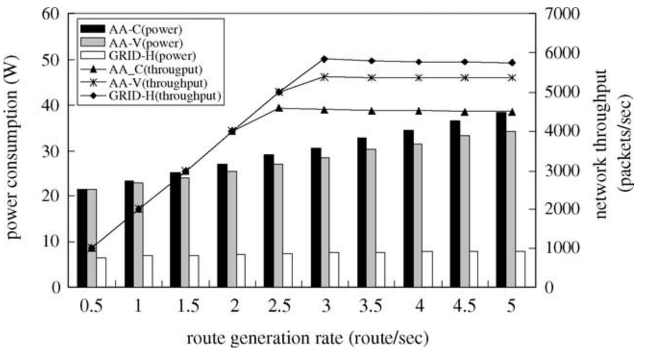


Fig. 8. Power consumption and network throughput vs. route generation rate (number of hosts = 300, inter-grid phase = 75%, speed = 10 m/s).

4. Conclusions

In this paper, we have proposed a new power-saving architecture for MANETs. Based on a grid structure, the framework addresses the energy conservation issue on several protocol layers, including physical layer, medium access control, power mode management, and network layer. On all these layers, the location information of mobile hosts is exploited. Our solution is an integrated one compared to existing solutions, which are only power-aware and location-aware on some of these aspects. The results can significantly extend the lifetimes of mobile hosts. The key contributions of this work include an energy-aware leader election protocol for the grid structure, and an efficient superframe structure to support intra-grid and inter-grid communications.

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