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A Partitioned Power and Location Aware MAC Protocol for Mobile Ad Hoc Networks

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Abstract—This paper proposes a novel power and location aware medium access control (MAC) protocol, called LAMP (Location Aware MAC Protocol). LAMP is designed for location aware mobile ad-hoc networks (MANETs). LAMP uses the concept of cellular geographical division of the network in order to build a distributed time division multiple access (TDMA) based schedule for transmission, reception and sleep. It allows hosts to avoid overhearing the network and instead sleep and conserve power. Power saving is a significant concern in MANETs as most mobile hosts operate with a limited amount of power available to them. LAMP trades an increase in latency for a reduction in energy consumption, whilst maintaining fairness in the network. The proposed MAC protocol allows hosts to reduce energy consumption by powering their radio transceivers off whilst still maintaining a responsive and fair network. As in cellular networks this approach uses location information to partition the network into hexagonal cells. Once a host knows which cell it is in and can synchronize its clock, it can build a TDMA based transmission and reception schedule. This is a novel advancement over empirically tuned low duty cycle power conservation, as it not only intelligently minimizes power consumption but also avoids interference.

Keywords— *Ad Hoc Networking, MAC Layer, Location Aware, Power Efficient*

I. INTRODUCTION

MANETs have been proposed as the underlying network “infrastructure” for a wide range of possible network centric applications, ubiquitous computing, sensor networking and intelligent environments to mention a few. In actuality there is no network “infrastructure” in MANETs. The hosts themselves are the network infrastructure, and they communicate amongst themselves in a multi-hop fashion. Because of this property the duration and stability of the network depends on the hosts and several factors affecting them. Some factors such as mobility are beyond the network designer’s control. However the longevity and stability of the network can be vastly increased by an improvement in the hosts’ usage of power resources.

In MANETs the devices are not just concerned with their own ability to communicate, but also play an integral role as enablers of the communication of other devices within the network. In this mode of operation a

device’s energy consumption is dominated not by data processing, but instead by wireless communication[1]. The proposed MAC protocol is designed to use location information in order to make wireless communication in a MANET more ordered, hence less ad-hoc, and in this way increase its efficiency whilst maintaining fairness.

In a shared medium network is necessary to provide fair access to the medium to all nodes. The medium access control (MAC) protocol is used to decide which hosts are allowed access the medium and at what time. A key feature of good MAC protocols is the avoidance of interference through collisions. Collisions occur when two interfering nodes attempt to transmit at the same time. Many MAC protocols have been developed for wireless communications networks and they are divided into three broad categories: Allocation protocols; contention protocols and hybrid protocols, which contain elements of both[2]. The protocol presented here is a hybrid protocol.

This paper investigates the design of a MAC protocol which is both power conserving and location aware, and in fact acquires its power-conserving features from its location awareness.

II. BACKGROUND

In order to facilitate the development of large MANETs reducing power consumption on all layers becomes a key goal. While sending information over a wireless interface consumes the significant proportion of power, idling and listening also consume substantial amounts of energy too[3]. The two major problems that MAC protocols in MANETs attempt to overcome are known as the hidden node problem and the exposed node problem.

A hidden node is one that is within the range of the intended destination but out of range of the sender. In this case whilst the sender is sending its message to the destination, a hidden node can sense the medium and find that it is idle. However when the hidden node transmits, its signal will collide at the destination and the destination will lose the message that was being sent by the initial sender due to interference.

The exposed node problem is complementary to hidden node problem. An exposed node is one that is within the range of the sender but out of range of the destination. The sender begins transmitting its message to the destination when the exposed node senses the medium it will find that the medium is busy and is unable to transmit a message. In the exposed node problem the medium is underutilized.

The current approach to overcoming these problems is typified by the IEEE 802.11 DCF protocol[4]. In such CSMA/CA based protocols, RTS and CTS control packets inform nodes when to be quiet to avoid interfering with a transmission. With the knowledge of the nominal broadcast radius and the knowledge of a nodes location it is possible to create a “forbidden zone” where nodes remain quiet to avoid collision.

Current approaches to creating efficient MAC protocols for ad hoc networks have centered on the use of low duty cycle radio algorithms[1, 3]. These algorithms are based around cycling the radio interface of the node from listening to off periodically in order to maintain connectivity throughout the network. S-MAC[3] uses periodic sleeping to reduce the power consumption of the network. It also requires that nodes form clusters and synchronise their sleep cycles. This approach to power awareness in ad-hoc networks can be thought of as “self-organising”. The MAC protocol described herein is instead “pre-organised” based on a common understanding of location and timing information by the nodes of the network.

III. MAC LAYER DESIGN

The MAC protocol presented here is a hybrid protocol. It combines elements of both allocation and contention protocols. Whilst the TDMA based allocation protocol described here is a product of geometrical reasoning, the contention component is still to be decided upon, however some options are presented here. Essentially the TDMA allocation protocol developed here works for a single host per cell. However it is unreasonable to assume that there is only one host per cell, and as a result a contention protocol is introduced inside the TDMA structure.

A. TDMA

A prerequisite for the described MAC protocol is that all nodes are location aware, that is they have access to either a global or local geographical co-ordinate system[5-7]. Nodes are either enabled with GPS locators[8] or are able to use the network infrastructure to determine their location[5, 6]. It is also necessary that all nodes within the network are synchronized in the time domain in order to build coherent transmission and reception schedules. This synchronization can be achieved through the methods used for geographic awareness, GPS for instance provides consistent clocks[7] alternatively time stamping can be used to overcome clock drift[3]. The knowledge of geographical

information by nodes within a MANET is not an unreasonable assumption. Wireless sensor networks are an interesting application that use MANET infrastructure, the information gathered by sensor networks is much more useful when coupled with geographical information, and as a result nodes would need to have this information available to them in order to report it. The current generation of mobile phones are equipped with GPS sensors in order to improve their location awareness[9], and there is on going research into improving GPS indoors[10].

To form a cellular structure within a MANET a mapping is used to convert geographic locality to hexagonal grid cells[8]. Hexagonal grids are the obvious choice for modeling cellular networks as they provide a close approximation to the actually circular circumference of an omnidirectional transmission radius, while being able to be arranged in a regular cell structure. Hexagonal grids are often used in the design of cellular communications networks. The co-ordinate system of the hexagonal grid is based on a 60 degree x,y axis, where each cell has a mapping from GPS based geographical co-ordinates to cellular co-ordinates (i,j) .

To ensure connectivity throughout the cellular grid, the logical grid size is determined such that any host in a particular grid cell is able to communicate with any other host that resides in its own cell or any of its six neighbouring grid cells. Let l be the side length (or radius) of the regular hexagonal cell and r be the nominal transmission radius of the radio interface. The relationship shown in equation 1 guarantees intercellular communication. This now means that any a host in any particular cell can communicate in two ways: intracellularly, to hosts residing in the host’s own cell and intercellularly to hosts residing in neighbouring cells.

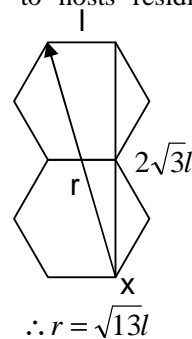


Figure 1. Derivation of the relationship between broadcast radius and cell size.

$$l = \frac{r}{\sqrt{13}} \quad (1)$$

The use of the nominal transmission radius in the calculation of a cellular structure makes it possible to determine the effects transmissions from different cells will have on the level of interference in the network.

This knowledge at a cellular level allows the development of a TDMA based schedule for transmission, reception and sleep which allows fairness and avoids overhearing (redundant sensing of the medium).

Given a coordinated cellular structure it is now possible to build a transmission schedule that uses this information. Overhearing and interference within the network can be avoided by building a transmission and reception schedule which avoids hidden and exposed nodes in the network in order to minimize interference during transmission. To accomplish this, a repeating pattern based on the six fold symmetry of hexagons is found in the network. In figure 2 notice that host x which is on the corners of cells S , D and C but resides in cell S is transmitting, its signal is able to reach all the hosts in its own cell as well as all the hosts in its neighbouring cells, due to the defined geometry of the cell structure. This means that host x 's signal will be received in the cells A - F but specifically host y in cell A . If the signal from x is received at y it will also be received at z a host which is not in a cell neighbouring S . The geometry of the hexagonal cellular structure allows the definition of a set of cells that constitute a "forbidden zone" in the network. This "forbidden zone" contains cells whose hosts are unable to transmit as their transmissions would cause interference to ongoing communications. The "forbidden zone" is the set of cells that are within 2 cells of a receiving cell. Using this property it is possible to determine which cells must not transmit when a host in a particular cell is receiving. When a cell is broadcasting to its six neighbours, the cells which are also allowed to broadcast at the same time to avoid interference are those that lie four cells away from it on the following axes; $+x$, $-x$, $(+x,+y)$, $(+x,-y)$, $(-x,-y)$, $(-x,+y)$. So if a cell with coordinates $(0,0)$ is transmitting cells with coordinates $(4,0)$, $(-4,0)$, $(4,4)$, $(4,-4)$, $(-4,-4)$, $(-4,4)$ are also allowed to transmit, see figure 3. Using this symmetry it is possible to divide the network into supercells containing 16 cells, see figure 4.

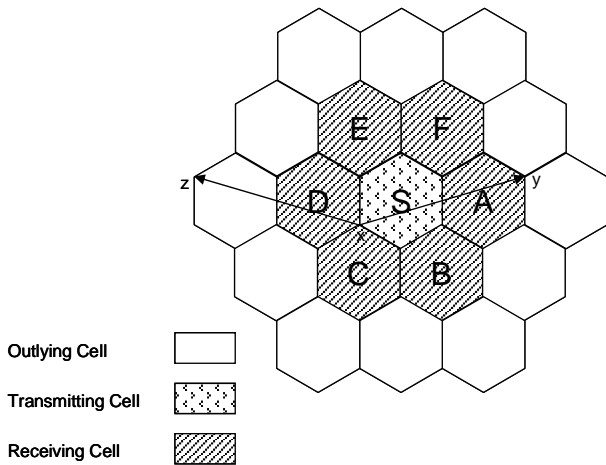


Figure 2. Cellular transmission overlap caused by cell geometry.

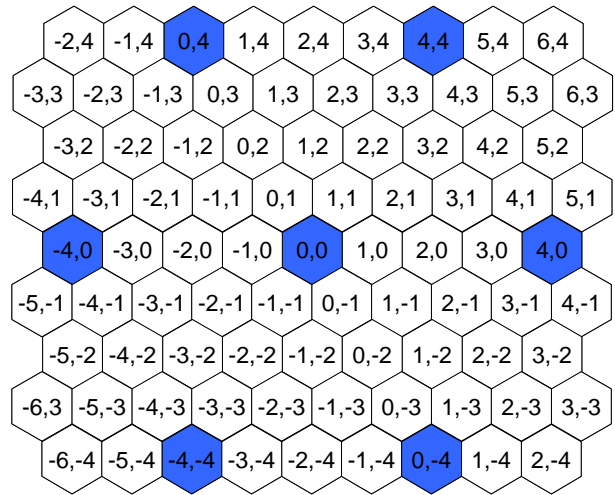


Figure 3. Marked cells are allowed to broadcast

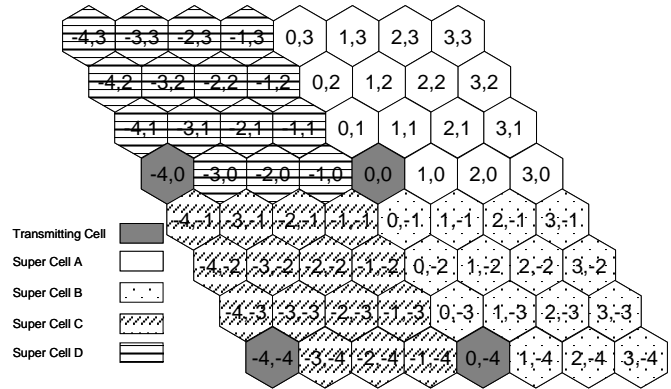


Figure 4. Supercell coordinates

Each cell within each supercell is given an identifier based on its coordinates (i,j) . The network can now be co-coordinated in such a way that when one cell 0 is transmitting all other cell 0 's are also transmitting. The function presented below gives cells identifiers in the range from 0 to 15 after taking in the cell coordinates (i,j) as input.

```
function ID (i,j)
  x = i mod(4)
  if (x < 0)
    x = x + 4
  y = j mod(4)
  if (y < 0)
    y = y + 4
  ID = i + (4*j)
return ID
```

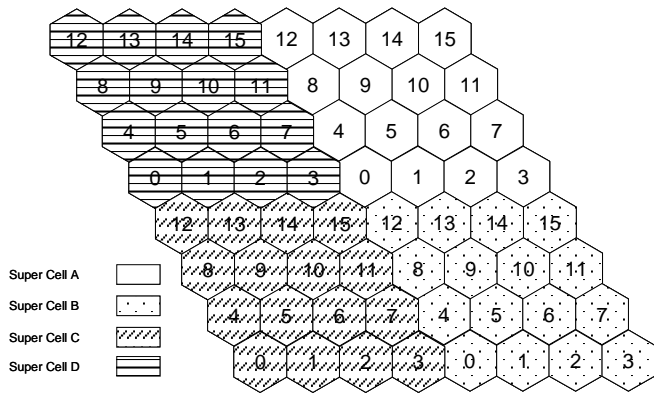


Figure 5. Supercells with Cell IDs

This means that hosts within a cell can find the cell IDs of the neighbouring cells based on the following functions of its ID and its cell coordinates.

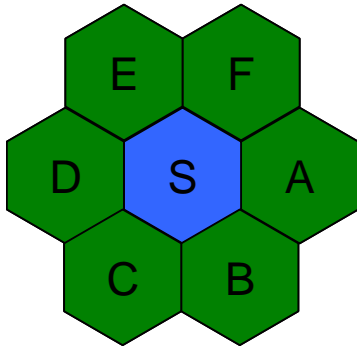


Figure 6. Cell S and its neighbouring cells.

```
function A (ID,j)
  y = (j)mod(4)
  if (y < 0)
    y = y + 4
  A = (ID + 1)mod(4) + (y * 4)
  return A

function B (ID)
  B = (ID + 12)mod(16)
  return B

function C (ID)
  if ((ID) mod(4) == 0)
    C = (ID + 15)mod(16)
  else
    C = (ID + 11)mod(16)
  return C
```

```
function D (ID,j)
  y = (j)mod(4)
  if (y < 0)
    y = y + 4
  D = (ID + 3)mod(4) + ((j)mod(4)* 4)
  return D
```

```
function E (ID)
  E = (ID + 4)mod(16)
  return E
```

```
function F (ID)
  if ((ID) mod(4) == 3)
    F = (ID + 1)mod(16)
  else
    F = (ID + 5)mod(16)
  return F
```

Hence a cell with coordinates (0,0) whose ID is 0 has neighbour's whose identifiers are A = 1, B = 12, C = 15, D = 3, E = 4, F = 5.

Once a host has found its own cellular ID and the cell IDs of its neighbouring cells it can now calculate a transmission, reception and sleeping schedule. This could be done purely on the IDs themselves, however this gives a nasty property that traffic traveling along the +x axis will travel much faster than traffic traveling along the -x axis, as first cell 0 would transmit, followed by cell 1, etc. The IDs are used instead to calculate the schedule based on the following permutation function.

```
function transtime(ID)
  TT = (ID * 7)mod(16)
  return TT
```

This means that hosts in cell 0,0 will transmit at time 0 and listen to it's neighbours at times A = 7, B = 4, C = 9, D = 5, E = 12, F = 3. See figure 7.

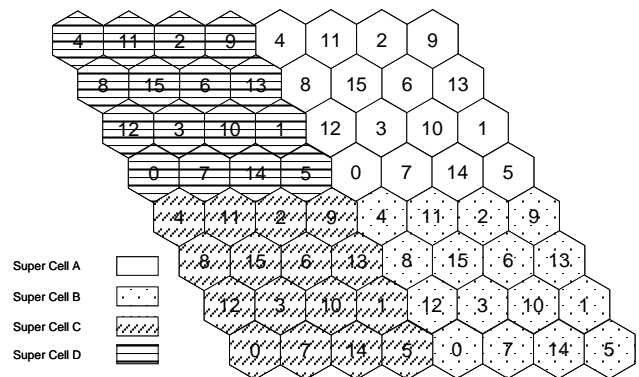


Figure 7. Supercells with each cell's transmission time number.

As each cell has an ID based on a sixteen cell repeating pattern a TDMA frame is made of sixteen timeslots see figure 8.

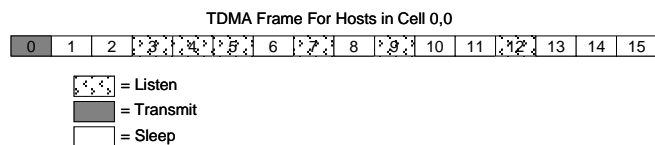


Figure 8. TDMA Frame.

This means a nominal schedule ratio of transmit/receive/sleep is 1/6/9. This allows each host in the network to build a consistent distributed TDMA frame, given that they know which cell of the network they are in (their location) and have a consistent clock.

B. CONTENTION

In order to ensure connectivity throughout the network two modes of communication must be supported: communication between nodes in the same cell (intracellular communication) and communication between nodes in different cells (intercellular communication). To this end each slot is divided into two periods, the intracellular period and the intercellular period.

There are two conceivable approaches to managing communications at this level: A distributed approach whereby a distributed algorithm is used to determine which host in a cell is allowed to transmit or a centralized approach where one cell is nominated to coordinate the hosts' communications. I shall concentrate on the centralized approach as the cellular partitioning of the network conveniently provides clusters (the cells). There have been many routing algorithms [8, 11-13] that use clusters and cluster gateways to route messages through the network. The cluster gateway will now be responsible for coordinating network communications at the MAC layer.

1) Intracellular Communications

In a centralized architecture an obvious choice for intracellular communications would be 802.11 PCF [4]. In this scenario the gateway host would act as a point coordinator (PC) and poll the hosts residing in its cell allowing them access to the medium. The intracellular period in this case is divided into 2 smaller periods, one where the gateway host is allowed to transmit without contention and one where hosts within the cell are polled using PCF.

Another approach would be to have hosts contend to access the medium. This could be accomplished in one of two ways. The intracellular period is divided into 2 smaller periods, one where the gateway host is allowed to transmit without contention and one where hosts

contend using a CSMA/CA protocol. Another approach is to divide the intracellular period into 3 smaller periods, one where the gateway host is allowed to transmit without contention, one where hosts can contend for reservation, one where the reservations made in the previous period are used.

The suitability of different approaches can only properly be determined through simulation. It is important to note that power can be conserved on intracellular communications as the broadcast radius required to reach all hosts within a cell is $2/\sqrt{13}$ of the nominal broadcast radius. Hence less power is required by transmitting hosts during the intracellular period.

The gateway host election process also occurs during the intracellular period. There are several mechanisms proposed in literature for host election [8, 12, 14]. These are usually based on broadcasts of suitability criteria within the cluster, whereby the most suitable host in a cluster becomes the gateway host. Some of the criteria that would be important for a gateway host are relatively large supply of power, proximity to the cell centre and computing capacity.

2) Intercellular Communications

In a centralized system the gateway host can be made responsible for all intercellular transmissions. Intercellular communications can occur in a number of ways. Essentially there are two variants that are considered here. Each has advantages and disadvantages.

a) Variant 1

The intercellular period is divided into 7 smaller periods. One period is available for intercellular broadcast. This is a broadcast that will be received by all the hosts in the broadcaster's own cell as well as all the hosts in the six neighbouring cells. The next 6 periods are used for unicast communications to each of the transmitting cell's neighbouring cells A-F.

There are several key advantages of this variant. Intercellular unicast communications with each neighbouring cell is ensured in each frame. This promotes connectivity throughout the network. It further reduces the amount of time hosts in neighbouring cells need to listen to the medium, as they can only be contacted during 2 of the sub periods of their neighbouring hosts' intercellular period, the broadcast and the directed unicast. A host knows which of its neighbouring cells A-F it is listening to at a given time, it can thus determine which cell A-F it is in relative to the transmitting cell, e.g. to its cell A it will be cell D.

The most important advantage however is that because of the uniform nature of the transmissions throughout the network, if a cell has no data to unicast to a particular neighbour, this transmission period can be contended for. The cells that are allowed to contend for the channel are known as the transmission set which includes the cells which are neighbours to the transmitting cell and also neighbours to the cell which was to be unicast to. This contention could take place in

a reservation slot and the original transmitter could broadcast the victor to the three contending cells after which a transmission could take place. The potential receiving cells of this transmission are the cells in the transmission set and the original transmitting cell. The transmission and reception sets are calculated so as not to interfere with other transmissions in the network. In this instance cells in the transmission set should only contend if they have data to transmit to cells in the reception set. In this way a transmission period that would have been wasted can potentially be used.

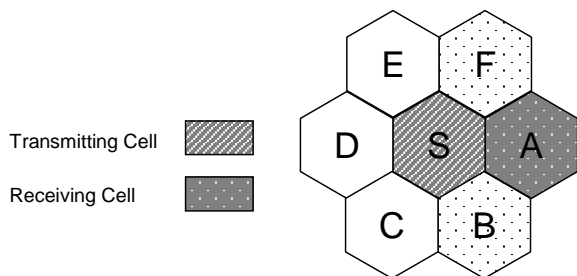


Figure 9. Cells F, A, B are members of the transmission set. Cells S, F, A, B are members of the reception set.

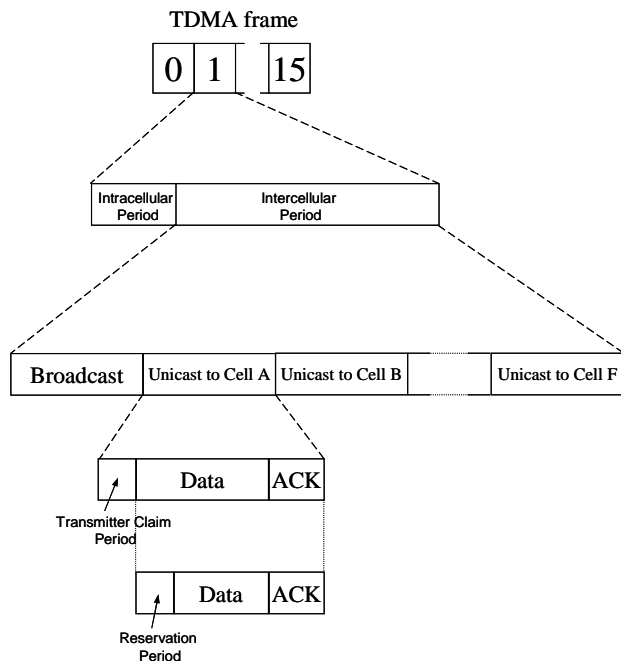


Figure 10. The integration of TDMA and contention using Variant 1.

The most obvious disadvantage of this scheme is that it increases latency in the network as the intercellular

period must be long enough to accommodate unicast communications with all neighbouring cells. It is also possible that often these unicast periods will not be utilized, even when contention is used. Simulation is necessary to determine the suitability of variant 1 under different traffic models.

b) Variant 2

Variant 2 is a more simplistic scheme. The intercellular period is divided into only 2 smaller periods: one for broadcast communication to all neighbouring cells and one for a unicast to a single cell. In the header of the broadcast packet the transmitter nominates which cell it will be unicasting to in the following unicast period. If the transmitter has no information to broadcast it can instead use this period as if it were a unicast period as long as it still nominates which host it will unicast to in the following period.

There are several advantages of this scheme. The intercellular period is shorter, and hence the overall TDMA frame is shorter, which means there is less latency in the network. Power is also conserved as although all hosts must listen to the broadcast period, if they are not the target of the unicast they can sleep. Overall it is a simpler scheme.

The obvious disadvantages are that hosts are not able to unicast to each cell in a single TDMA frame. At most it is possible to unicast to only 2 of the cell's six neighbouring cells in a single TDMA frame. Also if a station has no data to transmit, none of the neighbouring cells are able to contend for the channel as it would cause interference. As with variant 1, variant 2 requires simulation to determine its suitability.

DISCUSSION

Interference within ad-hoc networks is very closely related to the geographic location of the hosts. The MAC protocol design presented uses location awareness to decrease the contention and interference overhead in the network. It is a power conserving whilst still responsive and fully connected. As compared to power saving MAC protocols such as S-MAC[3] in which every host has a 50% duty cycle, the presented MAC protocol is a vast improvement. If it is assumed that the intracellular period lasts as long as the intercellular period, non-gateway hosts sleep at all times except during their cells intracellular period, that is a 3.125% duty cycle. The activity of the gateway hosts depends on the contention mechanism chosen. In the worst case, gateway hosts still sleep for during 9 slots in the 16 slot TDMA frame, which is lower than a 50% duty cycle.

CONCLUSION

This paper has presented the preliminary design for a power aware MAC protocol for location aware MANETs. There are certainly still several issues which need to be investigated. At the technical level the control packet and data packet formats need to be decided. The

length of the different periods (intercellular, intracellular, etc) need to be determined, however these lengths are dependant on the physical layer specifications. At an analytical level the proposed MAC protocol and its variants need to be analysed mathematically in order to ratify their apparent feasibility. The performance of this protocol and its variants should be investigated through simulation. A comparison could then be made to show its performance relative to current MAC protocols.

The presented MAC protocol is designed to improve the communications within location aware ad-hoc networks. However only analysis and simulation will be able to tell to what degree the improvement is.

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