Adaptive Asynchronous Sleep Scheduling Protocols for Delay Tolerant Networks

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Abstract—In this paper, we focus on power management for Delay/Disruption Tolerant Network (DTN), and propose two asynchronous clock-based sleep scheduling protocols that are distributed, adaptive, and energy efficient. Moreover, the sleep schedules can be constructed using simple systematic algorithms. We also discuss how the proposed protocols can be implemented in mobile devices for adapting to dynamic network conditions in DTN. Theoretical analysis is given to demonstrate the energy efficiency and scalability of the proposed protocols. Simulation results show that the proposed protocols reduce the energy consumption in the idle listening mode up to 35 percent in comparison with other existing asynchronous clock-based sleep scheduling protocols, and more than 90 percent compared with the protocol without power management, while maintaining comparable packet delivery delay and delivery ratio.

Index Terms—Delay tolerant network, power management, asynchronous sleep scheduling, mobility.

1 Introduction

Recently, considerable research efforts have been put to Delay/Disruption Tolerant Network (DTN) [1], [2], [3], [4], [5], [6], [7] to enable communications between disconnected network entities. DTN architecture is characterized by frequent disruptions and long delayed connections due to mobility, sparse deployment of nodes, node failures, and noises, etc. Unfortunately, many mobility scenarios in DTN depend on mobile devices that have limited energy capacity, and the fundamental problem is that traditional power saving mechanisms are designed assuming well-connected networks. For a sparsely connected network, time durations between contacts are generally much larger than contact durations for more than a order of a magnitude [8], which indicates that nodes spend most of their life time in the idle listening mode and centralized power saving strategies are difficult. Experimental studies in [9], [10] show that power consumption in an idle listening mode is almost as high as in a receiving mode. Consequently, a large amount of energy, over 95 percent of the total energy [11], is consumed by the idle listening mode searching for neighbors, rather than by infrequent data transfers. Therefore, it is essential to have distributed power saving protocols for DTN that is distributed and effective at reducing energy consumption in the idle listening mode to minimize the degradation of network connectivity and to maximize the benefits from mobility.

Many power saving mechanisms have been proposed for various network architectures and at different layers of wireless network protocol stack [12], [13]. Generally, existing power saving mechanisms can be categorized into three types: on-demand wakeup, scheduled wakeup, and asynchronous wakeup. For on-demand wake up mechanisms, mobile nodes are equipped with a secondary low power radio module to wake up its radios to be ready for data exchange. For example, a separate signaling lower power radio [14] or a RFID tag [15] can be used to wake up the device for data exchanges. For scheduled wakeup mechanisms, nodes in the network wake up at synchronized intervals to communicate with each other. IEEE 802.11 PSM [16] is the most well-known synchronous power saving protocol originally designed for single hop networks. Wireless devices, called nodes, with synchronized clocks, periodically turn on or off their radio to save energy. This process is called a *duty cycling* or a *sleep scheduling*. For multihop wireless networks, nodes can cooperatively coordinate their wake schedules to increase the energy efficiency of the network while maintaining sufficient connectivity for required bandwidth [17]. However, these protocols assume that nodes are synchronized by global synchronization algorithm. For asynchronous wakeup mechanisms, nodes connect with each other by waking up at predetermined time intervals that guarantee overlap with awake intervals of neighboring nodes [18], [19], [20]. Asynchronous wakeup mechanisms do not require synchronized clocks, and they are suitable in scenarios where global clock synchronization is impossible or impractical to realize. Furthermore, there exists a performance trade-off between energy efficiency and neighbor discovery ratio for different cycle lengths of the sleep schedules. The performance can be further improved if each node can adaptively use a sleep schedule that optimizes the individual performance requirement. Adaptive sleep scheduling mechanisms provide a set of sleep schedules with different cycle lengths that guarantee overlapping awake intervals between any pair of sleep schedules [21], [22], [23], [24], [25], [26].

There have been some efforts to provide power management in DTN. Optimal searching/probing intervals are calculated using mean and variance of contact durations and waiting times in knowledge-based mechanism [27] and using distribution of contact duration and bursty nature of number of new contacts in STAR [28]. Under opportunistic contacts, with synchronized clocks, beacon intervals are

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adaptively adjusted in AEB [29]. An asynchronous clock-based sleep scheduling protocol is proposed in CAPM [30], where sleep schedules are determined based on node densities and traffic load requirements. These adaptive protocols balance the trade-off between energy consumption and connectivity to improve performance considering dynamic node mobility characteristics. In addition, on-demand wakeup mechanisms for DTN are proposed in [11], [31]. In sum, previous power management protocols in DTN focus on constructing policies or architectures to increase contact opportunities. However, these protocols either require global clock synchronization which is difficult to accomplish in sparsely connected multihop networks or use frame structures that are not energy efficient due to frequent beacons and long idle listening intervals.

In this paper, we first study asynchronous clock-based sleep scheduling protocols in multihop wireless networks. Then, we propose adaptive asynchronous sleep scheduling protocols for DTN, which provide multiple levels of power saving and are energy efficient under intermittent connectivity for minimizing energy consumption. Moreover, the adaptive power saving levels (PSLs) can be constructed using simple systematic algorithms. Finally, several implementation issues considering the unique characteristics of DTN and approaches to maximize energy efficiency are discussed. Both theoretical analysis and simulation results are given to evaluate the performance of the proposed protocols in comparison with other existing adaptive asynchronous sleep scheduling protocols. Theoretical analysis results demonstrate that the proposed protocols are more energy efficient while guaranteeing required connectivity. Simulation results using *NS-2* [32] verify that the proposed protocols, while maintaining similar packet delivery delay and delivery ratio, can reduce the energy waste in the idle listening mode up to 35 percent.

The remainder of the paper is organized as follows: we first present a comprehensive survey of existing asynchronous sleep scheduling protocols in multihop wireless networks in Section 2. We define our system model in Section 3. After presenting preliminaries of adaptive asynchronous sleep scheduling protocols in Section 4, we propose two new adaptive asynchronous sleep scheduling protocols for DTN in Section 5, and discuss implementation issues in Section 6. The performance of the proposed protocols is evaluated using theoretical analysis in Section 7 and simulations in Section 8. Finally, the paper is concluded in Section 9.

2 Related Work

In this section, asynchronous sleep scheduling protocols in Mobile Ad hoc Network (MANET) and DTN are presented. They can be classified into nonadaptive or adaptive protocols depending on their ability to provide multiple power saving levels.

2.1 Nonadaptive Asynchronous Sleep Scheduling Protocols

Quorum-based Protocol (QPS) [18] is the first work in the asynchronous sleep scheduling protocols. Assuming equal sized intervals, called *slots*, QPS guarantees at least two overlapping active intervals between two nodes while being awake $(2\sqrt{n}-1)$ slots out of n slots. This is achieved by each node using an active schedule set that is formed by arbitrarily choosing a row and a column from a square n space, as shown in Fig. 1a.

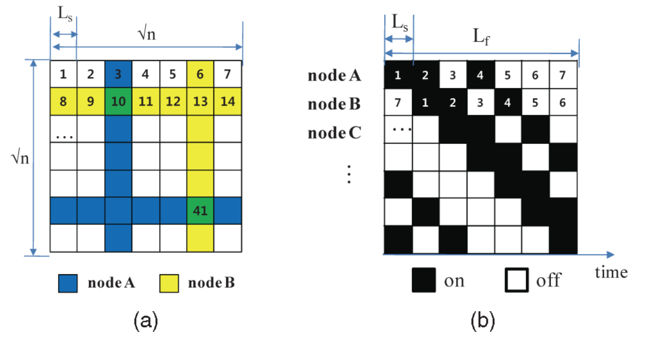

Fig. 1. Asynchronous Sleep Scheduling Protocols. In QPS, the schedules of A and B have overlapping active slots at slots 10 and 41. In CDS, the active slot 2 of schedule A is overlapping with the active slot 1 of schedule B. (a) Quorum based ($n = 49$). (b) Cyclic difference set based ($v = 7$).

More energy efficient sleep schedules are constructed in Cyclic Difference Set-Based Protocol (CDS) [20], [33] by using cyclic difference sets in combinatorial mathematics. The construction of difference sets is a projective plane problem with parameters $(v, k, \lambda) = (q^2 + q + 1, q + 1, 1)$ where a set consisting of v total slots constructed with k active slots guarantees at least one overlapping active slot. The difference set used by the CDS provides the theoretically minimum active slot ratio. As shown in Fig. 1b, one overlapping slot is guaranteed between any two sets. In addition, CQPM [34] that has similar concepts to QPS and CDS is also independently proposed.

2.2 Adaptive Asynchronous Sleep Scheduling Protocols

The drawback of QPS and CDS is their failure to guarantee overlapping active slots between sets with different sizes. In other words, nodes may not be able to discover each other if sets with different sizes are used. Therefore, they cannot adjust to network dynamics, such as traffic load, topology, or node mobility to further optimize performance. To overcome this problem, several adaptive asynchronous sleep scheduling protocols have been proposed. There exists a trade-off between the number of active slots per set and the required minimum number of slots to guarantee at least one overlapping active slot between two different sets. Adaptive protocols exploit this trade-off to increase energy efficiency by adjusting sets sizes depending on the network condition.

Based on QPS, AQPS [22], and AQEC [21] allow different nodes to use individual ns to provide an adaptive power saving. However, as in QPS, each n must be a perfect square, and active slot ratio of sets are twice the optimal active slot ratio provided by CDS [22]. In DTN, CAPM [30] determines the sleep schedule based on known node densities and traffic load requirements. Although the determined sleep schedules are fixed and not adaptive, we classify CAPM as an adaptive protocol since the sleep schedule of CAPM that achieves the lowest active slot ratio is the same as the sleep schedule of AQEC, as will be explained in Section 7.1.

TABLE 1
Index of Terms

Symbol	Description
Frame Structure	
E_i	list of active elements of set i
n_i	number of slots in set i
L_s	length of a slot
L_f	length of a frame ($= L_s \times n_i$)
L_A	length of the ATIM window
Definitions	
$C_{h,m}(E_i)$	set i repeated to m slots with a shift
$RCP\{E_i, E_j\}$	rotational closure probability between set i and set j
Implementation Issue	
T_{ICD}	inter-contact duration
T_{CD}	contact duration
T_{SD}	slot delay duration
T_R	data exchange duration
P_i	power saving level i
Performance Evaluation	
P_c	contact probability
R_i	active ratio of set i
NS_{ij}	neighbor sensitivity between set i and set j

Based on CDS, AAPM [23] provides an adaptive power saving by constructing a collection of pairs, called an *AA-quorum space*. Although AAPM achieves active slot ratios close to the optimal active ratio, the eligible values in the *AA-quorum space* must be a prime number. Moreover, we will show in Section 7.1 that AAPM is only effective for small ns ($n \leq 47$).

Based on *cyclic read-write coteries* used for managing replicated data, ACQ [24], [25] constructs two levels of power saving for clustered ad-hoc networks: a symmetric-quorum (s-quorum) and an asymmetric-quorum (a-quorum). ACQ allows the nodes using the s-quorum to discover other nodes using the s-quorum or the a-quorum. However, the nodes using the a-quorum cannot discover other nodes using the a-quorum.

Most recently, HQS [26] provides a generalization of QPS that constructs sets with arbitrary cycle lengths using a projection concept. At least one overlap of awake interval between any two set is guaranteed within a projected cycle length. Two algorithms, Extended Grid HQS (EGHQS) and Difference Set HQS (DSHQS), are proposed. Although they are adaptive, we show in Section 7.1 that the active slot ratio of EGHQS is close to AQEC and the active ratio of DSHQS is close to the optimal active ratio for small ns, such as $n \leq 25$. The projection algorithms used in HQS become inefficient as n increases. Therefore, HQS is more suitable for static and densely deployed ad-hoc networks that require fine-tunable cycle lengths.

3 System Model

3.1 Network Model

We consider a graph represented by $G = (V, E)$, where the vertex set V contains N mobile nodes and the edge E is defined by the connectivity between nodes. Due to frequent link disconnections and dynamic topology in DTN, E varies with time. Links are undirected and symmetric. If node i and node j are within communication range of each other at time t, $e_{ij}(t) = e_{ji}(t) = 1$, otherwise, $e_{ij}(t) = e_{ji}(t) = 0$. Contact schedules among nodes are not known in advance, and nodes can exchange messages only if they are connected.

3.2 Sleep Scheduling Model

Each node follows a predetermined combination of active and inactive time intervals, called a *sleep schedule*, that are successively repeated. A complete cycle of the sleep schedule is called a *frame*, and its length is denoted by L_f. A frame may consist of unequal sized intervals as in [30] or equal sized intervals, called *slots*, forming a *set* as in [21], [23], [24], [26], [33]. For the protocols with unequal sized slots, let L_{on} and L_{off}, respectively, represent the duration of active intervals and inactive intervals. Similarly, for the protocols with equal sized slots of lengths L_s dividing a frame into $N_s = L_f/L_s$ slots, let N_{on} and N_{off}, respectively, represent the number of active slots and inactive slots. L_A, is the length of the Announcement Traffic Indication Message (ATIM) window length required to exchange connection setup messages (Beacon-ATIM-ATIM Response) as defined in [16].

3.3 Performance Metric

The main objective of adaptive asynchronous sleep scheduling protocols is to provide required connectivity with high energy efficiency. The energy efficiency is measured by the active ratio which describes how often the node is in active mode, and the required connectivity is measured by the neighbor sensitivity which describes how well the node finds a neighboring node within its transmission range.

3.3.1 Active Ratio

The active ratio, R, is defined for a given frame of length L_f with unequal sized slots as

$$\begin{aligned} R &= L_{on}/L_f, \\ L_f &= L_{on} + L_{off}, \end{aligned} \tag{1}$$

and for a given frame of length L_f with equal sized slots as

$$\begin{aligned} R &= N_{on}/N_s, \\ N_s &= L_f/L_s = N_{on} + N_{off}. \end{aligned} \tag{2}$$

3.3.2 Neighbor Sensitivity

The neighbor sensitivity, NS, is the worst-case delay for a node to detect a new node within its coverage. In asynchronous sleep schedules, the NS is determined by the minimum frame size that guarantees at least one overlapping slot between two different schedules. Table 1 gives the summary of important symbols used in the paper, and Table 2 gives the summary of adaptive asynchronous sleep scheduling protocols including the active ratio and the neighbor sensitivity.

4 Preliminaries

4.1 Cyclic Difference Set

The *difference set* is designed such that for v total slots, called a *block*, with k "on" slots, there are exactly λ overlapping "on" slots among k different blocks. If the set of blocks is a square matrix with each of k elements appearing once in

TABLE 2
Summary of Adaptive Asynchronous Sleep Scheduling Protocols

Protocol	Year	Active Ratio	Neighbor Sensitivity	Remarks
AQPS [22]	2005	$\geq\sqrt{2n}/n$	$L_s \times n$	Adaptive version of QPS [18, 19] based on a torus system [35].
AQEC [21]	2006	$R_{QEC(\sqrt{n_i})}=(2\sqrt{n_i}-1)/n_i$ where $0\leq n_i \leq n_j$	$L_s \times (n_j-\sqrt{n_j}+1)$	Similar to AQPS [22]. Requires n to be a square of an integer.
CAPM [30]	2007	$R_{CAPM(\sqrt{n})}\geq(2\sqrt{n}-1)/n$	$L_s \times (n-\sqrt{n}+1)$	Frame structure similar to AQEC [18].
ACQ [24]	2007	a-quorum: $R_{ACQ(n)}=p/n$ s-quorum: $R_{ACQ(n)}=(\phi+q-1)/n$ where $1\leq\phi\leq n$, $p=\lceil n/\phi\rceil$, $q=\lceil(n+1)/2\phi\rceil$	$L_s \times n$	Overlap not guaranteed among a-quorums.
AAPM [23]	2007	$R_{AAPM(n_i)}\approx\sqrt{n_i}/n_i$ where $0\leq n_i\leq n_j$	$L_s \times n_j$	Adaptive space is limited to prime n for $n \leq 47$.
EGHQS [26]	2008	$R_{EGHQS(n_i)}=(\phi_i+q_i-1)/n_i$ where $0\leq n_i\leq n_j\leq n_{d-1}$, $\phi_i=\min\{\lfloor\sqrt{n_i}\rfloor,\lceil\sqrt{(n_{d-1}+1)/2}\rceil\}$, $q_i=\lfloor n_i/\phi_i\rfloor$	$L_s \times (n_j+\phi_i-1)$	Similar to AQEC [21], but allows any n using a projection algorithm.
DSHQS [26]	2008	$R_{DSHQS(n_i)}=(\phi+q_i-1)/n_i$ where $0\leq n_i\leq n_j\leq n_{d-1}$, $\phi=\lceil\sqrt{(n_{d-1}+1)/2}\rceil$, $q_i=\lceil(n_i+1)/2\phi\rceil$	$L_s \times (\lfloor(n_i-1)/2\rfloor+n_j+\phi-1)$	Adaptive version of CDS [20] using a projection algorithm.
EACDS	2009	$R_{EACDS(i)}=(k_I(k_E)^i)/(v_I(v_E)^i)$, $n_i=v_I(v_E)^i$ where $0\leq i\leq j$	$L_s \times n_j$	I and E are difference sets.
MACDS	2009	$R_{MACDS(i)}=(k_I k_{Mi})/(v_I v_{Mi})$, $n_i=v_I(v_{Mi})$ where $0\leq i\leq j$	$L_s \times n_j$	I and M_i are difference sets. Active ratio close to the optimal.

every block, this design is called a *symmetric design* as defined below.

Definition 1 (Symmetric Design). *A set with v elements and k subset elements $D: a_1, \ldots, a_k \pmod v$ is called a symmetric (v,k,λ)-difference set if and only if the sets $B_i: a_{1+i}, a_{2+i}, \ldots, a_{k+i} \pmod v$, $i=0,\ldots,v-1$ are a cyclic (v,k,λ) block design.*

The blocks of a symmetric design are a cyclic shift of each other, and the difference set satisfying the symmetric design property is called a *cyclic difference set* as formally defined below.

Definition 2 (Cyclic Difference Set). *A set with v elements and k subset elements $D: a_1, \ldots, a_k \pmod v$ is called a (v,k,λ)-difference set if for every $d \neq 0 \pmod v$ there are exactly λ ordered pairs (a_i, a_j), $a_i, a_j \in D$ such that $a_i - a_j = d \pmod v$.*

The cyclic shift property of cyclic difference sets allows overlapping slots under any cyclic time shifts. An example using the cyclic difference set $(7,3,1)$ is illustrated in Fig. 2.

The construction of cyclic difference sets follows the Singer's Theorem [36] as given in (3)

$$(v,k,\lambda) = \left(\frac{q^{n+2}-1}{q-1}, \frac{q^{n+1}-1}{q-1}, \frac{q^n-1}{q-1}\right). \tag{3}$$

From (3), a cyclic difference set exists for some prime power q and some positive integer n. For a special case with $n=1$, the difference set becomes a projective plane problem. Then, the (3) becomes

$$(v,k,\lambda) = (q^2+q+1, q+1, 1). \tag{4}$$

The possible cyclic difference sets with $\lambda = 1$ using the Singer's theorem is given in Table 3. Note that for any particular set of parameters v, k, and λ satisfying Definition 2, there are no other difference sets having these parameters.

The cyclic difference set design problem in combinatoric is formulated for asynchronous sleep scheduling protocols in CDS [20], [33]. A row of a block of length v, representing a frame of length L_f consisting of v slots of length L_s, have overlapping intervals combined to the length of a slot within L_f even if the slot boundaries are not synchronized under time shifts. The advantage of CDS in comparison with other asynchronous sleep scheduling protocols is that it constructs frames with the lowest active ratio. However, the drawback is that the sleep schedules are not adaptive. They are designed for ad-hoc network with high node degree and low mobility, and its nonadaptive structure is unsuitable for DTN which has long delayed intermittent connections and dynamic mobility. An adaptive structure is suggested in CDS using *superposition* of sets to reduce beacon pollution. However, a super-frame of length v^2 is created from a frame of length v, and the difference in frame sizes becomes too large to be practical for a large v.

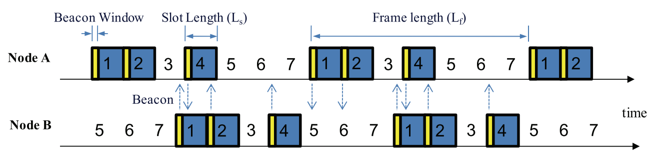

Fig. 2. An example of overlap of slots between two nodes using $E_{(7,3,1)} = \{1,2,4\}$ under cyclic clock shifts. Slot 4 of node A is partly overlapping with slots 1 and 2 of node B.

TABLE 3
Possible Cyclic Difference Sets ($\lambda = 1$)

v	k	λ	Set Sequence	Active Ratio
7	3	1	1 2 4	0.429
13	4	1	1 2 4 10	0.308
21	5	1	1 2 5 15 17	0.238
31	6	1	1 2 4 9 13 19	0.194
57	8	1	1 2 4 14 33 37 44 53	0.140
73	9	1	1 2 4 8 16 32 37 55 64	0.123
91	10	1	1 3 7 8 19 22 32 55 64 72	0.110
			etc.	

4.2 Rotational Closure Property

Since nodes are not synchronized to wakeup periodically in an asynchronous clock-based environment, an important requirement of asynchronous sleep scheduling protocols is the *rotational closure property* [22] that is satisfied between two sets if they have at least one overlapping slot within a cycle length of n for any cyclic shifts. This property allows two nodes to discover each other even under different time shifts. In order to describe this requirement, we define a *rotational closure probability* which represents the probability of existence of at least one active slot between two different schedules for all possible cyclic shifts. RCP between sets E_i and E_j for $n_i \le n_j$ is formulated as

$$RCP\{E_i, E_j\} = \left(\sum_{h=0}^{n_i} \theta_h \right) \bigg/ n_i, \tag{5}$$

$$\theta_h = \begin{cases} 1, & \text{if} \quad C_{h,n_j}(E_i) \cap C_{0,n_j}(E_j) \neq \emptyset, \\ 0, & \text{if} \quad C_{h,n_j}(E_i) \cap C_{0,n_j}(E_j) = \emptyset, \end{cases}$$

where $C_{h,m}(E)$ is an *extended cyclic set* which represents a set E repeated to length m with a cyclic shift h. If $RCP\{E_i, E_j\} = 1$, then E_i and E_j are called *rotational sets*, and the rotational closure property is satisfied between the two sets. If $RCP\{E_i, E_j\} < 1$, E_i and set E_j are not rotational sets, indicating that there exist cyclic shift cases where two sets do not have an active overlapping slot. Note that, for two same sets, $RCP = 1$, but for two different sets, $RCP \le 1$. If two different sets have $RCP = 1$, then they are called *adaptive sets*, otherwise, they are *nonadaptive sets*. For example, between (21, 5, 1) and (13, 4, 1), $C_{0,21}(21,5,1) \cap C_{9,21}(13,4,1) = \{1,2,5,15,17\} \cap \{6,10,11,13,19\} = \emptyset$ and $C_{0,21}(21,5,1) \cap C_{6,21}(13,4,1) = \{1,2,5,15,17\} \cap \{3,7,8,10,16,20,21\} = \emptyset$. Therefore, for all possible shifts, $RCP\{(21,5,1),(13,4,1)\} = 11/13$, and they are nonadaptive sets.

5 Adaptive Cyclic Difference Set System

In well-connected traditional ad hoc networks, the cycle lengths of adaptive sleep schedules need to be relatively small and fine-grained to provide short end-to-end delays [26]. However, in DTN with sparsely connected nodes, the cycle lengths are relatively large, up to several seconds in many DTN scenarios, since small cycle lengths waste energy without discovering many more contacts [30], [31]. Also, the main source of energy waste that needs to be reduced is caused by the idle listening problem. Therefore, in this section, we propose Adaptive Cyclic Difference Set protocol that constructs two different types of sleep schedules suitable for DTN. ACDS is designed with multiple power saving levels that are energy efficient for large cycle lengths.

5.1 Construction of Exponential ACDS

In this section, Exponential ACDS (EACDS) is proposed. The basic strategy is to use hierarchical arrangements of sets. As shown in Fig. 3a, a difference set called an initial set at power saving level 1 ($P_1 = I = (v_I, k_I, \lambda_I)$) is scaled by another difference set called an exponential set ($E = (v_E, k_E, \lambda_E)$) to create a hierarchical set with power saving level 2 (P_2). The hierarchical set can be scaled again with E to create yet a higher level hierarchical set P_3 which provides higher energy efficiency than P_2 at the cost of lower contact opportunities. The scaling is done by the Kronecker product, also called a direct product, denoted by $\otimes$. It operates on two matrices of arbitrary size resulting in a block matrix as defined below.

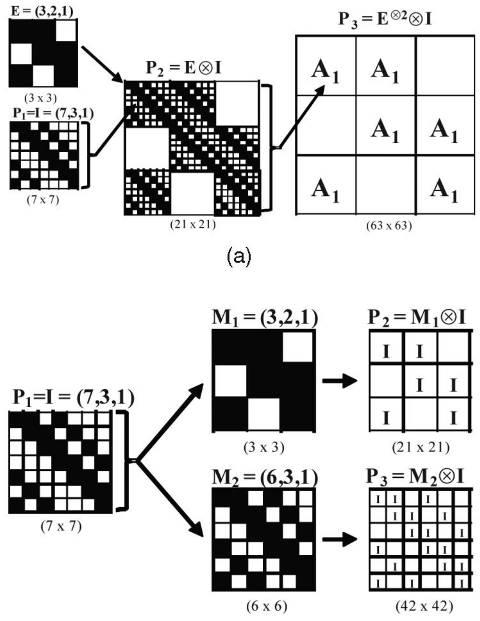

Fig. 3. Construction of Adaptive Cyclic Difference Set System (ACDS). (a) Exponential adaptive CDS. (b) Multiplicative adaptive CDS.

Definition 3 (Kronecker Product). *Let $A = (a_{ij})$ be a $m \times n$ matrix and $B = (b_{kl})$ be a $p \times q$ matrix. Then, the Kronecker product of A and B is the $mp \times nq$ block matrix $C = (c_{\alpha\beta}) = a_{ij}b_{kl}$ where $\alpha = p(i-1)+k$ and $\beta = q(j-1)+l$*

$$C = A \otimes B = \begin{bmatrix} a_{11}B & \dots & a_{1n}B \\ \vdots & \ddots & \vdots \\ a_{m1}B & \dots & a_{mn}B \end{bmatrix}. \tag{6}$$

In our design, A is the scaling set (E) and B is the initial set (I). Let nth Kronecker power of A be the n-fold Kronecker product of A with itself, i.e.,

$$A^n = \prod_n \otimes A. \tag{7}$$

Then, the hierarchical sets can be expressed as $P_1 = I$, $P_2 = E \otimes I$, and $P_3 = E^2 \otimes I$.

For each block of size $v = v_I v_E^n$, EACDS guarantees that there is at least one overlapping slot between different blocks of size less than or equal to v as proved in Theorem 1.

Theorem 1 (Rotational Closure Property of the Exponential Hierarchical Design). *Given two sets $P_i = E^{i-1} \otimes I$ and $P_j = E^{j-1} \otimes I$ where $i \le j$. For $n = v_I v_E^j$, $C_{a,n}(P_i) \cap C_{b,n}(P_j) \neq \emptyset$, $\forall a,b : 0 \le a,b \le n$.*

Proof. Case 1-Perfect Alignment of Slot Boundaries. For $i = j = 1$, two sets are cyclic difference sets with set I. Therefore, there is at least one overlapping slot in $n_j = v_I$. For $i = 1$ and $j = 0$, $P_2 = E \otimes I$ and $P_1 = I$. I can be viewed as is a slot of $E \otimes I$ with a length v_I. Then, there is at least one overlapping slot of length v_I in $n_j = v_I v_E$. Since I is a cyclic difference set, there is at least one overlapping slot within v_I. For $i = j = 1$, two sets are cyclic difference sets with set E with slots of I. Then, there is at least one overlapping slot of length v_I in $n_j = v_I v_E$, and consequently, at least one overlapping slot within v_I. This can be proved for larger i and j by recursion.

Case 2-Imperfect Alignment of Slot Boundaries. Suppose that the difference in the clock shift of two set is δ, and length of a slot is L_s. Since P_i and P_j are cyclic difference sets, for an imperfect alignment of slots of δ, there exist overlapping sections $(L_s - \delta)$ and δ. The combination of $(L_s - \delta)$ and δ is equal to L_s. □

Therefore, the progressive hierarchial structure of EACDS always guarantees the rotational closure property between the different levels of hierarchy as well as between the same level.

5.2 Construction of Multiplicative ACDS

In this section, multiplicative ACDS (MACDS) is proposed. The basic strategy is to use hierarchical arrangements of sets as in EACDS, but a multiplier set ($M = (v_M, k_M, \lambda_M)$) is used instead of an exponential set (E). As shown in Fig. 3b, the initial set ($P_1 = I$) is scaled by a multiplier set (M_1) to create a hierarchical set ($P_2 = M_1 \otimes I$) and scaled by another multiplier set (M_2) to create another hierarchical set ($P_3 = M_2 \otimes I$). M_1 and M_2 are in the same hierarchical level but have different ns. For the frame of size $n = v_I v_M$, there is at least one overlapping slot between different sets with sizes less than or equal to v. This is because the multiplier sets belong to a *rotational sets group* which is defined below.

Definition 4 (Rotational Set Group). *A group of difference sets, $M = \{M_1 = (v_{M1}, k_{M1}, \lambda_{M1}), M_2 = (v_{M2}, k_{M2}, \lambda_{M2}), \ldots, M_i = (v_{Mi}, k_{Mi}, \lambda_{Mi})\}$ is called a rotational set group if $RCP\{M_i, M_j\} = 1$ for all i and j.*

For example, $M_1 = (3, 2, 1)$ and $M_2 = (6, 3, 1)$ belong to the same *rotational set group* since there is at least one overlapping slot between M_1 and M_2 within six slots.

The following corollary give the rotational closure property among hierarchical sets generated using the *rotational set group* on I.

Corollary 1 (Rotational Closure Property of the Multiplication Hierarchical Design). *Given two sets $P_i = M_{i-1} \otimes I$ and $P_2 = M_{j-1} \otimes I$ where $v_{Mi} \leq v_{Mj}$ and $RCP\{M_i, M_j\} = 1$, there exists an overlapping interval of at least v_I in v_{Mj}. Therefore, similar to proof for Theorem 1, we can prove that for $n = v_I v_{Mj}$, $C_{a,n}(P_i) \cap C_{b,n}(P_j) \neq \emptyset, \forall a, b : 0 \leq a, b \leq n$.*

The sets satisfying the above condition can be included in the same rotational set group. However, finding the rotational set group is not straightforward. Same cyclic difference set is a rotational set. However, two different cyclic difference sets are not necessarily rotational sets. For example, $(15, 5, 1) = \{1, 2, 3, 4, 8\}$ repeated with $+5$ shift ($C_{5,30}(15, 5, 1) = \{6, 7, 8, 9, 13, 21, 22, 23, 24, 28\}$) has no overlap with $(30, 6, 1) = \{1, 2, 3, 4, 5, 10\}$. In this case, two nodes will never be able to discover each other. In addition, the sets in a group may not be necessary multiple of one another. For example, $(7, 3, 1)$ and $(13, 4, 1)$ are rotational sets. The groups can be found by an exhaustive search.

TABLE 4
Possible Relaxed Cyclic Difference Sets ($\lambda = 1$)

v	k	λ	Set Sequence
4	3	1	1 2 3
5	3	1	1 2 3
6	3	1	1 2 4
			...
12	4	1	1 2 4 8
			...
24	6	1	1 2 3 4 8 16
			...
48	8	1	1 2 3 6 10 21 27 37
49	8	1	etc.

From the example, the candidates for rotational sets are not limited to cyclic difference sets. The relaxed cyclic difference set [37] as defined below can also be used to construct sleep schedules. Different from the normal cyclic difference set, the relaxed cyclic difference set provides cyclic difference set for any $N_s = v$ as shown in Table 4.

Definition 5 (Relaxed Difference Set). *A set with v elements and k subset elements $D : a_1, \ldots, a_k \pmod{v}$ is called a relaxed (v, k)-difference set if for every $d \neq 0 \pmod{v}$ there are at least λ ordered pairs $(a_i, a_j), a_i, a_j \in D$ such that $a_i - a_j = d \pmod{v}$.*

In MACDS, the combination of (v_M, k_M, λ_M) is chosen from the rotational set group. For example, $M_1 = (3, 2, 1)$, $M_2 = (6, 3, 1)$, $M_4 = (12, 4, 1)$, and $M_5 = (24, 6, 1)$ can be grouped together in the same rotational set group, and adaptive power saving levels with $I = (57, 8, 1)$ can be constructed as $P_1 = (57, 8, 1)$, $P_2 = (171, 16, 1)$, $P_3 = (342, 24, 1)$, $P_4 = (684, 32, 1)$, and $P_5 = (1{,}368, 48, 1)$. Comparing EACDS and MACDS, MACDS is more energy efficient, while EACDS is more useful in scenarios where many power saving levels are needed. In addition, it is possible to use a combination of the two proposed protocols.

6 Implementation Issue

In this section, we discuss implementation issues considering sparse node density and mobility in DTN, including frame structure, neighbor discovery process, data exchange process, and optimizing power efficiency.

6.1 Asynchronous Frame Structure

As shown in Fig. 4, we follow the same frame structure as in CDS [20], [33] where in each node, a frame of length L_f consisting of multiple slots of length L_s is consecutively repeated. The combination of active and inactive slots are determined by the set constructed in Section 5. In order to discover other neighboring nodes, each node transmits a beacon message at the beginning of each active slot. If the beacon is heard by another node, a connection can be established between the two nodes by exchanging connection set up messages.

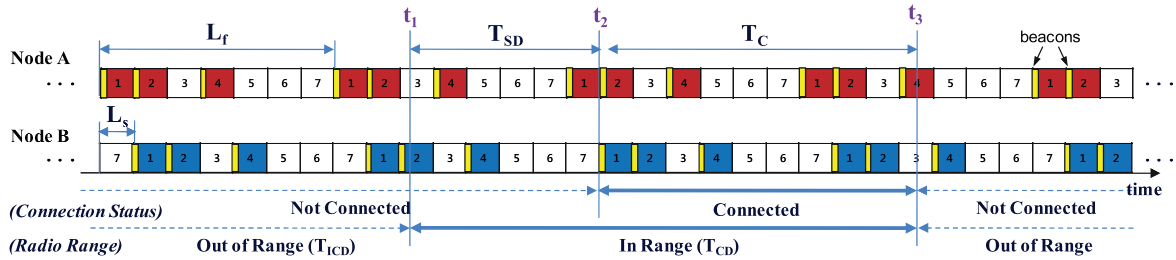

Fig. 4. Neighbor discovery in DTN. At t_1, nodes A and B come within range of each other. At t_2, after T_{SD}, active slots of each node overlap with each other, and they are able to exchange connection setup messages. At t_3, they move out of range with each other and are disconnected.

6.1.1 Minimum Slot Length

The slot length is directly associated with the energy efficiency ratio. In order to minimize energy consumption, the number of slots per frame should be maximized. However, the length of each slot has to be long enough to allow exchange of connection setup messages between contacted nodes. The length of each slot must be at least twice the length of the ATIM window:

$$L_s \geq 2L_A. \tag{8}$$

This condition ensures nodes to exchange necessary setup information with other nodes upon contact. For example, if the minimum L_A is 10 ms, then L_s has to be at least 20 ms. This necessary condition is explained in Corollary 2. Additionally, L_s may possibly be shortened, if partial exchange of connection setup messages can trigger the activation of the following slot.

Corollary 2 (Minimum Slot Length of Asynchronous Sleep Scheduling Protocol). *By Theorem 1, rotational sets always have overlapping intervals of duration* $(L_s - \delta)$ *and* δ *for the duration of the larger frame. Since* $\max\{(L_s - \delta), \delta\} \geq L_s/2$ *for* $\delta = (0, L_s)$, *nodes can exchange connection setup messages in either* $(L_s - \delta)$ *or* δ *if* $L_A \leq L_s/2$.

6.2 Neighbor Discovery in DTN

Neighbor discovery is responsible for finding other nodes in the network. In asynchronous sleep scheduling protocols, a connection can be established between two nodes within transmission range during common active slots. Although the exact location of the overlap is not known, the overlap is guaranteed with an upper bound NS which represents the worst-case delay for a node to detect a new node in its coverage.

In traditional multihop wireless networks with high node degree, NS determines the required one-hop delay as suggested in CDS [20]. However, in DTN, with mobile nodes having limited transmission range, a connection between two nodes can be established only if two nodes in motion have a sufficient common active interval to exchange messages before they move out of range of each other. As illustrated in Fig. 4, due to frequent disconnections and long delays between connections, nodes are often isolated, and alternate between an intercontact duration and a contact duration, represented by T_{ICD} and T_{CD}, respectively. T_{ICD} is determined by how sparsely the nodes are deployed in a given topology, and T_{CD} is determined by how fast the nodes are moving with given radio transmission range. Since T_{ICD} is much larger than T_{CD} [8], [11], [29], nodes are often disconnected and one-hop delays are negligible compared to T_{ICD}. Therefore, L_f is chosen depending on the NS that achieves the required contact probability rather than the required one-hop delay.

Contact probability is the ratio of successful connections among mobile nodes given a certain L_f, and it is dependent on the connection duration and the NS. The amount of time required for a node to have a overlapping slot with another node in range is called a slot delay duration, represented by $T_{SD} \leq NS$. Due to mobility of nodes and $T_{SD} \geq 0$, the actual connection duration, represented by T_C, is less than or equal to T_{CD}. Let T_R represent the required time duration to exchange all data packets between two nodes. Then, the condition $T_{CD} \geq (T_{SD} + T_R)$ must be satisfied to guarantee successful transmission of all packets. If $NS > T_{CD}$, two nodes might miss each other. On the other hand, if NS is too small, then nodes will consume unnecessary power during idle listening periods.

The achievable contact probability given a NS can be estimated using the CDF of T_{CD} under RWP model as in [38] or assuming a certain distribution of T_{CD} as in [28]. Fig. 5 shows the minimum T_{CD} required to achieve a certain contact probability under RWP model. For instance, the NS of nodes moving at 10 m/s needs to be less than $T_{CD} = 8$ s to achieve the contact probability above 0.95.

6.3 Adaptive Power Saving Levels

Multiple power saving levels have frames with different lengths that provide a trade-off between connectivity and energy efficiency. While well-connected traditional ad hoc networks require fine-grained multiple PSLs with relatively small frame sizes to minimize delays at each hop [26], sparsely connected DTNs require multiple PSLs, though they may be less fine-grained, to minimize idle listening periods. We define PSLs in ACDS as follows: the level with

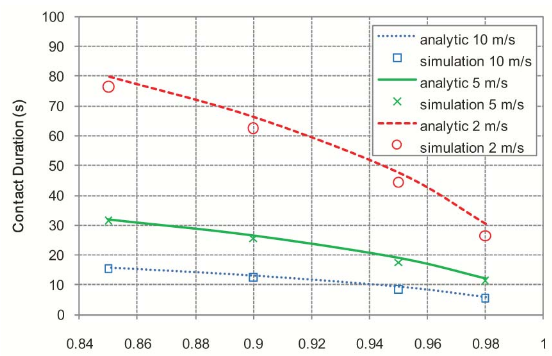

Fig. 5. Required contact duration for given contact probability under different node velocities. 20 mobile nodes with 250 m radio transmission range moving according to random waypoint (RWP) movement model within 3,000 m by 3,000 m area.

the initial set (I) is called PSL 1 (P_1). Here, L_f of P_1 is chosen so that it achieves the maximum required connectivity. Then, PSLs are labeled in an increasing order of frame lengths. Higher PSLs provide higher energy efficiency at the cost of lower contact opportunities.

Since we consider opportunistic contacts, contact times and durations are only known with some probability distribution [28], [39], [40]. As explained in the previous section, under sparse density of nodes, the delivery performance depends on the contact probability between nodes. Consider that nodes can approach each other at any angle, the distribution of T_{CD} is a function of speed and transmission range of nodes [38]. Therefore, given a fixed transmission range, PSLs can be selected based on the node speed.

6.3.1 Sleep Schedules of PSLs

We provide an example to show how sleep schedules of PSLs can be constructed given a range of node speeds v_{min} and v_{max} and a required contact probability P_c for a given routing protocol. In order to estimate the required range of NS, $\min(T_{CD})$ and $\max(T_{CD})$ are calculated between nodes moving at v_{max} and v_{min}, respectively, using a known mobility distribution or a mathematical approximation [38]. Since $T_{CD} \geq (T_{SD} + T_R)$, $\min(NS) = (\min(T_{CD}) - T_R)$ and $\max(NS) = (\max(T_{CD}) - T_R)$. If $\min(NS) = 8$ s and $\max(NS) = 80$ s, n_i for P_1 is $n_1 = \min(NS)/L_s = 400$. Next, we construct the sleep schedules using MACDS. A cyclic difference set which satisfies $v_I \leq n_1$ is chosen as $I = P_1$. Finally,

$$\begin{aligned} I &= \{381, 20, 1\} \text{ and } M = \{M_1, \ldots, M_8\} \\ &= \{(v_{M1}, k_{M1}, 1), \ldots, (v_{M8}, k_{M8}, 1)\} = \{(3,2,1), (4,3,1), \\ &\quad (5,3,1), (6,3,1), (7,3,1), (8,4,1), (9,4,1), (10,5,1)\} \end{aligned}$$

can be used to produce multiple PSLs $\{P_1, \ldots, P_9\} = \{(381, 20, 1), \ldots, (3810, 100, 1)\}$ having frame lengths from 7.62 to 76.2 s.

6.3.2 Selecting PSLs

A moving node can adaptively select the highest possible P_i that achieves desired contact probability. In addition, PSLs of the proposed protocol can also be integrated with existing searching/probing protocols. For example, PSLs can be selected using statistical information of contact duration and waiting times as in [27], [28], and can also adaptively selected by exploiting self-similarity of contact arrival rate as in [28], [29]. The minimum amount of time that a node needs to be awake to discover other nodes in order to achieve required contact probability is called an optimal searching/probing interval, and it is equivalent to NS in our paper.

6.4 Data Delivery Using Asynchronous Frames

After exchanging connection setup messages, some extra active slots may be needed for data exchange. As illustrated in Fig. 6, if a node is involved in sending or receiving connection setup messages or data packets in the current slot, the succeeding slot also becomes an active slot. The extension continues until the slot is not involved in any message exchange. This mechanism is called a *slot extension*. The number of extended slots is small for low traffic loads and large for high traffic loads. Therefore, the slot extension effectively minimizes the idle periods and the power consumption.

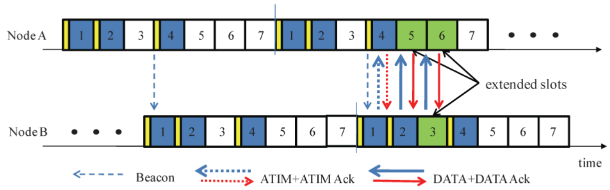

Fig. 6. Slot extension mechanism.

6.5 Compensating Synchronization Errors

In general, wireless devices are equipped with clocks that use hardware oscillators. However, imperfection of clock oscillators and external factors, such as temperature variation, supply voltage variation, and aging cause time inaccuracies, can cause time drifts. Typical error for a quartz crystal oscillator is between 10 and 100 ppm which corresponds to 10 to 100 μs of error per second. Consider that each node maintains a logical clock C. At time t_1, the time difference of two nodes, called a relative time drift, is $C_{ij}(t_1) = |C_i(t_1) - C_j(t_1)| \geq 0$. $C_{ij}(t_1)$ is equivalent to a constant time shift, and the rotational closure property for a constant time shift δ is proved in Section 5. However, if $C_{ij}(t_1)$ varies during a contact, the rotational closure property, which assumes a constant slot length L_s, does not hold. The additional time shift error needs to be compensated. The compensation can be accomplished using the following mechanism. If the maximum time drift error is ε ppm, each active slot additionally becomes active before and after its original active slot for $\varepsilon(t - t_1)$ where t_1 is the time at the beginning of each new frame. Therefore, each frame can compensate for the maximum time drift error and guarantees an overlapping period to be at least L_s.

7 Performance Analysis

In this section, the performance of the proposed protocols in comparison with existing adaptive asynchronous sleep scheduling protocols is analyzed. In specific, AQEC [21] and HQS [26] are considered for the direct comparison. Other existing adaptive asynchronous sleep scheduling protocols, CAPM [30], AAPM [23], and ACQ [24], are not considered in the comparison for the following reasons: CAPM shares the similar frame structure with AQEC, and the sleep schedule of CAPM that achieves the lowest active ratio is the same as the sleep schedule of AQEC; AAPM is limited to small set sizes, since the collection of sets that satisfy the rotational closure property is rare for $n > 50$, as shown in Fig. 7; ACQ is limited to two power saving levels and a-quorums fail to discover each other, as previously explained in Section 2. The active ratio (R) and the neighbor sensitivity (NS), as defined in Section 3.3, are compared in this section.

7.1 Comparison of Active Ratio

As a baseline for comparisons, the theoretical optimal active ratio provided by CDS [20] is given as

$$R_{CDS} = \frac{N_{on}}{N_s} = \frac{k}{v} = \frac{q+1}{q^2+q+1} \approx \frac{1}{\sqrt{N_s}}, \quad (9)$$

where q is a nonnegative integer.

AQPS [22] and AQEC [21] are based on QPS, and achieve active ratios approximately twice the optimal active ratio as

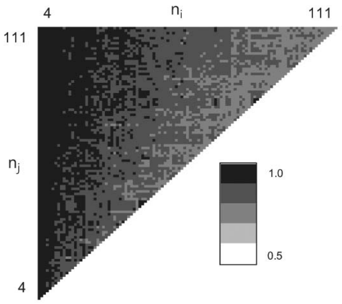

Fig. 7. RCP between all possible relaxed difference set pairs for $n_i < n_j \leq 111$.

$$R_{QPS} = \frac{N_{on}}{N_s} = \frac{2\sqrt{n}-1}{n} = \frac{2\sqrt{N_s}-1}{N_s} \approx \frac{2}{\sqrt{N_s}}. \tag{10}$$

CAPM [30] uses a frame structure that consists of equally spaced multiple short slots that are L_s long and L_c apart and one large slot that is L_c long. For given L_f and L_s, the active ratio of CAPM is

$$R_{CAPM} = \frac{L_s\left(\frac{L_f}{L_c}-1\right)+L_c}{L_f}. \tag{11}$$

R_{CAPM} is minimized when $L_c = \sqrt{L_f L_s}$. If we assume that the frame is divided into n slots of an equal length,

$$\min(R_{CAPM}) = \frac{L_{on}}{L_f} = \frac{2L_s\sqrt{n}-1}{L_s n}. \tag{12}$$

Since $L_f = n \times L_s$ and the length of each row is $L_c = \sqrt{n} \times L_s$ in AQEC, the sleep schedule of CAPM that achieves the lowest active ratio is the same as the sleep schedule of AQEC.

EGHQS and DSHQS presented in HQS [26] construct sets with arbitrary cycle lengths that guarantee rotational closure property between any two sets. In EGHQS, for any set i and set j with lengths less than or equal to the largest set n_{d-1}, $0 \leq n_i \leq n_j \leq n_{d-1}$, the sets are constructed by containing ϕ continuous elements followed by $q_i - 1$ interspaced elements with mutual distances less than or equal to ϕ, where $\phi_i = \min\{\lfloor\sqrt{n_i}\rfloor, \lceil\sqrt{(n_{d-1}+1)/2}\rceil\}$ and $q_i = \lfloor n_i/\phi_i \rfloor$. R_{EGHQS} is calculated for two different cases depending on the value of ϕ_i.

Case 1. If $\phi_i = \lfloor\sqrt{n_i}\rfloor$,

$$\begin{aligned} R_{EGHQS} &= \frac{N_{on}}{N_s} = \frac{\lfloor\sqrt{n_i}\rfloor + \left\lfloor\frac{n_i}{\lfloor\sqrt{n_i}\rfloor}\right\rfloor - 1}{n_i} \\ &\approx \frac{2\sqrt{n_i}-1}{n_i} \approx \frac{2}{\sqrt{n_i}} = R_{AQEC}. \end{aligned} \tag{13}$$

Case 2. If $\phi_i = \lceil\sqrt{(n_{d-1}+1)/2}\rceil$, and let $n_{d-1} = kn_i$ where $k \geq 1$ represents the size ratio between the set i and the largest set $(d-1)$,

$$\begin{aligned} R_{EGHQS} &= \frac{N_{on}}{N_s} = \frac{\left\lceil\sqrt{\frac{kn_i+1}{2}}\right\rceil + \left\lfloor\frac{n_i}{\lceil\sqrt{(kn_i+1)/2}\rceil}\right\rfloor - 1}{n_i} \\ &\approx \frac{k+2}{\sqrt{2k}}\frac{\sqrt{n_i}}{n_i} \geq \frac{2}{\sqrt{n_i}} = R_{AQEC}. \end{aligned} \tag{14}$$

Therefore, the active ratios of EGHQS and AQEC are approximately the same when $\lfloor\sqrt{n_i}\rfloor \leq \lceil\sqrt{(n_{d-1}+1)/2}\rceil$, and the active ratio is larger in EGHQS than in AQEC when $\lfloor\sqrt{n_i}\rfloor > \lceil\sqrt{(n_{d-1}+1)/2}\rceil$.

In DSHQS, for any set i and set j, $0 \leq n_i \leq n_j \leq n_{d-1}$, the sets are constructed by containing ϕ continuous elements followed by $q_i - 1$ interspaced elements with mutual distances less than or equal to ϕ, where $\phi = \lceil\sqrt{(n_{d-1}+1)/2}\rceil$ and $q_i = \lceil(n_i+1)/2\phi\rceil$. Let $n_{d-1} = kn_i$. Then,

$$\begin{aligned} R_{DSHQS} &= \frac{N_{on}}{N_s} = \frac{\left\lceil\sqrt{\frac{kn_i+1}{2}}\right\rceil + \left\lceil\frac{n_i+1}{2\lceil\sqrt{(kn_i+1)/2}\rceil}\right\rceil - 1}{n_i} \\ &\approx \frac{k+1}{\sqrt{2k}}\frac{\sqrt{n_i}}{n_i} \geq \frac{1}{\sqrt{n_i}} = R_{CDS}. \end{aligned} \tag{15}$$

Therefore, the projection algorithm used in HQS achieves active ratio close to the optimal active ratio for small k, but becomes inefficient as n_{d-1} increases. Particularly, $R_{DSHQS} > R_{AQEC}$ for $k > 6$.

ACDS provides multiple power saving levels using hierarchically arranged difference sets. Two proposed protocols, EACDS and MACDS, guarantee at least one overlap of active slot between any two set within the larger set (n_j). The active ratios of EACDS and MACDS, respectively, are

$$\begin{aligned} R_{EACDS} &= \frac{N_{on}}{N_s} = \frac{k_I(k_E)^p}{v_I(v_E)^p} = \frac{1}{\sqrt{N_s}}\frac{k_I(k_E)^p}{\sqrt{v_I(v_E)^p}}, \\ p &= \log_{v_E}(N_s/v_I), n \in \mathbb{Z}^+, \end{aligned} \tag{16}$$

$$R_{MACDS} = \frac{N_{on}}{N_s} = \frac{k_I k_M}{v_I v_M} = \frac{1}{\sqrt{N_s}}\frac{k_I k_M}{\sqrt{v_I v_M}}, \tag{17}$$

where v_I and k_I are, respectively, v and k of the initial set, v_E and k_E are, respectively, v and k of the exponential set, and v_M and k_M are, respectively, v and k of the multiplier set from the rotational set group. The active ratios of EACDS and MACDS are close to the optimal active ratio since a multiplication of parameters from two difference sets still generates a new difference set with a active ratio close to $1/\sqrt{n_i}$.

7.2 Comparison of Neighbor Sensitivity

From Table 2, NS is different for different protocols with the same n_i. For all protocols, NS between two different sets having n_i and n_j for $n_i \leq n_j$ is about n_j. In other words, two sets of different frame lengths have at least one overlapping active slot for the duration of the larger frame length. NS is exactly n_j for EACDS and MACDS, $(n_j - \sqrt{n_j} - 1)$ for AQEC, $n_j + \phi - 1$ for EGHQS, and $(\lfloor(n_i-1)/2\rfloor + n_j + \phi - 1)$ for DSHQS. As the number of slots increases, the effect of n_j for AQEC decreases exponentially but the effect of n_i for DSHQS increases linearly.

Overall comparison of active ratios with respect to NS is shown in Fig. 8. For a fair comparison, the largest set is $n_{max} = 1{,}368$. In EACDS, $I = (57, 8, 1)$ and $E = (3, 2, 1)$, and in MACDS, $I = (57, 8, 1)$ and M from the Section 5 are used. It can be seen that the active ratios of all protocols decrease as NS increases. The theoretical lower bound achieved by CDS is used as a reference. Note that the bound is only

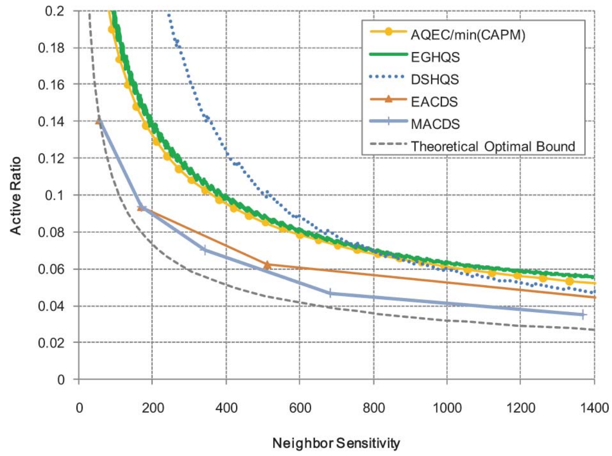

Fig. 8. Active ratios of different adaptive asynchronous protocols.

achievable for nonadaptive sets in CDS. The active ratios of AQEC, CAPM, EGHQS, and DSHQS are all approximately twice the optimal bound. The active ratios of EACDS and MACDS are closest to the optimal active ratio. The active ratio of DSHQS is higher than MACDS and even higher in lower ns. The higher active ratio in DSHQS is due to the fact that every set $n_i \leq n_{max}$ requires at least $\phi = \lceil \sqrt{(n_{max}+1)/2} \rceil$ active slots, which increases as n_{max} increases. In conclusion, although the set sizes of EACDS and MACDS are less fine-grained than other protocols, given required NS, the active ratios of existing protocols are similar while the active ratios of EACDS and MACDS are significantly smaller. Moreover, both EACDS and MACDS become more effective as the initial set size, v_I, increases.

8 Simulation Results

In this section, the performance of the proposed protocols is evaluated by simulation results. The Network Simulator (*NS*-2) [32], with additional implementations of the DTN packet forwarding mechanism, the spray and wait routing protocol [41], and the asynchronous sleep scheduling mechanism, is used for the simulation. The density of mobile nodes is configured to produce a sparse network with a contact ratio between 0.01 and 0.1 as demonstrated in real life experiments [28], [42], [43]. Flows are created between source nodes and destination nodes that are randomly chosen. Packets are generated at every packet generation interval throughout the simulation. The power consumption model is taken from [9] for 802.11 2 Mbps card. Each slot is at least twice the ATIM window size of 10 ms as explained in Section 6. Each node, once connected with another node, remains active until the data exchange is finished. The summary of parameters used in the simulation are given in Table 5. Only the results for MACDS are shown for simplicity.

The performance metrics used in the simulation are 1) energy consumption; 2) average packet delivery delay; and 3) packet delivery ratio. Energy consumption is the amount of power consumed by the operations of the wireless network interface. Average packet delay is the time delay of packets from source nodes to destination nodes. Since spray and wait routing protocol generates multiple copies of the same packet, the delay of the first arriving packet at the destination among multiple copies is considered. Packet delivery ratio is the number of packets received by the destination nodes divided by the number of packets generated by the source nodes.

TABLE 5
Simulation Parameters

Parameter	Value
Simulation Time	20000 s
Map Size	5000 m x 5000 m
Movement Model	Random Waypoint
Routing Protocol	Spray and Wait [41]
MAC Protocol	CSMA/CA based
Spray size	2 duplicates
Node Parameters	
Number of Nodes	20
Node Speed	1.0-32.0 m/s
Pause Time	30 s
Radio Range	250 m
Bandwidth	2 Mbps
Flow Parameters	
Number of Flows	20
Beacon Frame Size	40 bytes
Data Packet Size	1000 bytes
Packet Generation Interval	5.0-80.0 s
Message Timeout	10000 s
Power Consumption Model [9]	
Transmit Mode (P_{tx})	1.3272 W
Receive Mode (P_{rx})	0.9670 W
Idle Mode (P_{idle})	0.8437 W
Sleep Mode (P_{sleep})	0.0664 W

8.1 Impact of Node Speed

The performance of different PSLs using MACDS under various node speeds is given in this section to demonstrate the effect of different nodes speeds on the selection of PSLs. All nodes move at the same speed and packet generation interval is 60 s. The performance is compared with the constant access mode (CAM), where the node is in the idle mode when it is not in transmit or receive mode. The sleep schedule parameters used for PSLs in MACDS are shown on Table 6. Beacon period of 1.0 s is used in CAM to match the frame length of P_1 in MACDS which provides the highest contact probability in MACDS.

8.1.1 Energy Consumption

As shown in Fig. 9a, when the node speed increases, the energy consumption increases slightly. Faster moving nodes have more opportunities to contact other nodes, and more packets can be exchanged between nodes. As expected, nodes using higher PSLs achieve higher power savings due to lower active ratios. The energy consumption in P_5 is 50 percent of P_1 and 11 percent of CAM, respectively.

TABLE 6
Sleep Scheduling Parameters for MACDS

PSL	N_s	N_{on}	M	L_f (s)
P_1	57	8		1.14
P_2	171	16	$(3,2,1)$	3.42
P_3	342	24	$(6,3,1)$	6.84
P_4	684	32	$(12,4,1)$	13.68
P_5	1368	48	$(24,6,1)$	27.36

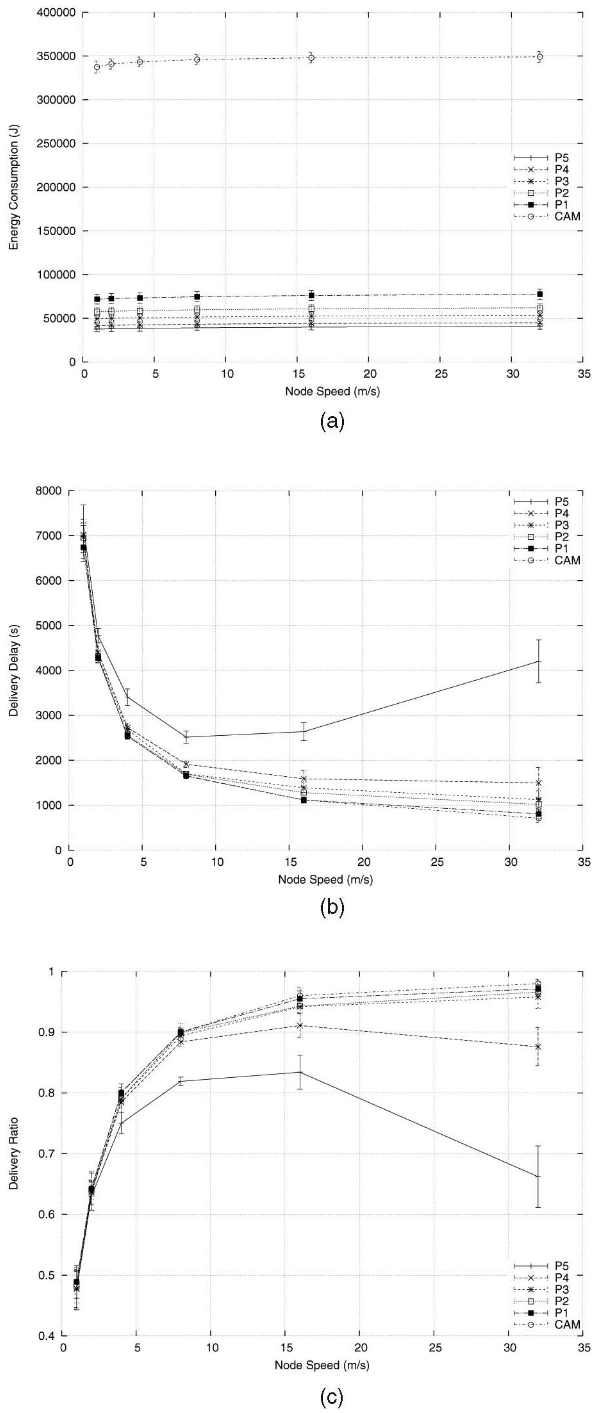

Fig. 9. Impact of node speed. (a) Energy consumption. (b) Average packet delay. (c) Packet delivery ratio.

To provide a more detailed evaluation of the energy consumption, the breakdown of energy consumption by different power states is given in Fig. 11a. It can be seen that the ratio of energy consumption in transmit and receive modes are much lower than that in idle and sleep modes. Nodes spend much more time waiting for contacts than actually being connected with other nodes. There is a slight increase of energy consumption in transmit and receive modes at higher node speeds due to the increase in packet transmission opportunities. In addition, the ratio of idle energy consumption in P_5 is lower than that in P_1. The result shows that the major source of power saving in higher PSLs is due to the reduction of energy consumption in the idle mode.

8.1.2 Average Packet Delivery Delay

As shown in Fig. 9b, the average packet delivery delay initially decreases as node speed increases, but increases at high node speeds. Slower moving nodes have longer intercontact durations, and messages are stored for longer periods. Therefore, for lower node speeds, the delay is constrained by the moving speed of nodes. On the other hand, faster moving nodes have shorter intercontact durations, but they also have shorter contact durations available for neighbor discovery. Therefore, for higher node speeds, the effect of contact probability on the delivery delay is greater. Also, we can see that higher PSLs have higher delays and are more sensitive to the increase in node speeds. Longer sleep intervals decrease the contact probability, and consequently, increase the average packet delay.

8.1.3 Packet Delivery Ratio

As shown in Fig. 9c, when the node speed increases, the delivery ratio initially increases, but decreases at high node speeds. At low node speeds, nodes do not have many contact opportunities with other nodes in the network due to large intercontact durations to forward packets to destination nodes within the message timeout or the simulation time. Also large intercontact durations occur at high node speeds due to low contact probability.

Overall, the simulation results in this section demonstrate that a significant amount of energy can be saved by the sleep scheduling protocol and there exist a trade-off between different PSLs. Slower moving nodes with longer contact durations can use larger frames with lower active ratios to further reduce energy consumption. For example, P_5 consumes about 50 percent of power consumed in P_1 while maintaining the delay and delivery ratio close to P_1. However, for fast moving nodes, lower PSLs should be used to limit the performance degradation to the required level. Therefore, PSLs should be carefully chosen to optimize the performance as discussed in Section 6.

8.2 Impact of Traffic Load

In order to demonstrate the effectiveness of the adaptive sleep scheduling protocols, different groups of nodes with different node speeds are simulated under various traffic loads. The performance of MACDS is compared with AQEC and HQS. Two groups of nodes with different node speeds employ different power saving levels. As demonstrated by the previous simulation results, slower moving nodes can use longer frames to save more energy while maintaining contact ratios similar to that without a power saving mode. Required NS to achieve contact probability above 0.95 for nodes moving at 10.0 m/s and 1.0 m/s are 2.0 and 12.0 s, respectively. For a fair comparison, a common $L_s = 20$ ms is used, and sleep scheduling parameters of each protocol are assigned to achieve similar NS. The exact parameters used in the simulation are shown in Table 7. Here, n_{d-1} is used for EGHQS and DSHQS are 600 and 400, respectively. Note that NS is not exactly the same for each protocol. N_s of AQEC must be a perfect square, N_s of DSHQS and EGHQS

TABLE 7
Sleep Scheduling Parameters

Protocol	Group	NS	N_s, N_{on}	L_f(s)
AQEC	1	91	100, 19	2.0
	2	601	625, 49	12.20
EGHQS	1	100	92, 18	1.84
	2	600	577, 47	11.54
DSHQS	1	100	58, 16	1.16
	2	601	392, 28	7.84
MACDS	1	100	100, 12	2.0
	2	600	600, 36	12.00

can be any positive integer but some value of NS may not be available for all positive integers, and N_s of EACDS and MACDS are multiples of the initial set size.

8.2.1 Energy Consumption

As shown in Fig. 10a, when the packet generation interval decreases, the overall energy consumption increases. The breakdown of energy consumption in Fig. 11b shows that at higher traffic loads, the energy consumptions in the transmit mode and the receive mode increase, and the energy consumptions in the sleep mode decrease. The largest energy is consumed in the idle listening mode and the second largest energy is consumed in the sleep mode. MACDS achieves the lowest energy consumption. Compared with the best performing protocol, MACDS consumes 25 percent less total energy and about 35 percent less idle energy.

8.2.2 Average Packet Delivery Delay and Packet Delivery Ratio

Packet delay is higher and delivery ratio is lower for higher traffic loads due to 1) limited radio resources, and 2) packets generated near the end of simulation time not having sufficient time to forward packets to the destination. The packet delay and the delivery ratio, as shown, respectively, in Figs. 10b and 10c, are almost the same in all protocols. This is due to sparsely connected nodes achieving having NS values.

8.3 Effect of Power Consumption Model

From the theoretical analysis, the proposed protocols effectively reduce energy waste due to the idle listening problem by achieving low active ratios. However, due to nonzero power consumption in the sleep mode, the contribution of energy consumption by the sleep mode to the overall energy consumption grows significantly as the number of slots increases as shown in Fig. 11c. As the number of slots per frame increases, the ratio of active slots ($\frac{n+1}{n^2+n+1}$), corresponding to P_{idle}, exponentially decreases, whereas the ratio of inactive slots ($\frac{n^2}{n^2+n+1}$), corresponding to P_{sleep}, remains relatively constant. Therefore, the energy efficiency of the proposed protocols should be higher if a power consumption model having a smaller P_{sleep}/P_{idle} ratio is assumed. For example, if the power consumption model of Berkeley motes [44] with $P_{sleep}/P_{idle} < 0.01$ is used, the amount of energy saving in MACDS compared with the existing protocol further increases from 25 to 30 percent.

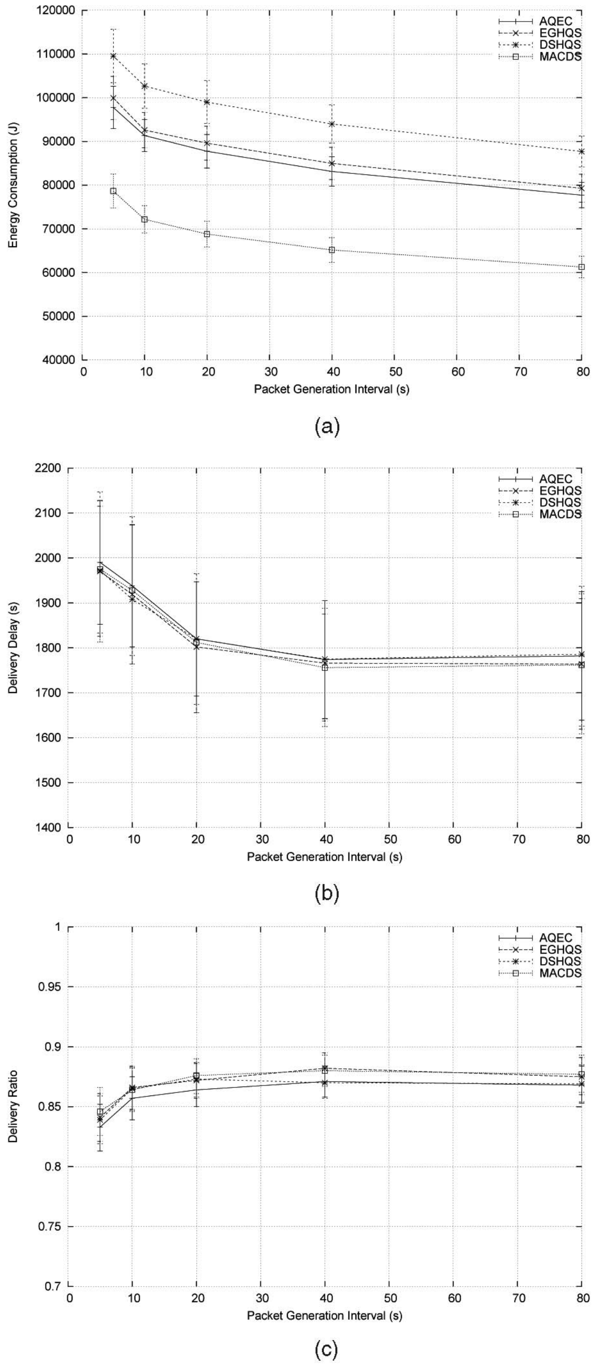

Fig. 10. Impact of traffic load. (a) Energy consumption. (b) Average packet delay. (c) Packet delivery ratio.

9 Conclusion

In this paper, energy efficient adaptive asynchronous sleep scheduling protocols, based on hierarchical arrangements of cyclic difference sets, have been proposed for DTN. Also, implementation issues to maximize energy efficiency in frame structure, neighbor discovery, and message exchange have been discussed. Theoretical analysis of active ratio and neighbor sensitivity has demonstrated the effectiveness of the proposed protocols, especially for large sleep schedules. Simulation results have shown that the proposed protocols, in comparison with other existing protocols, significantly reduce energy waste in the idle listening

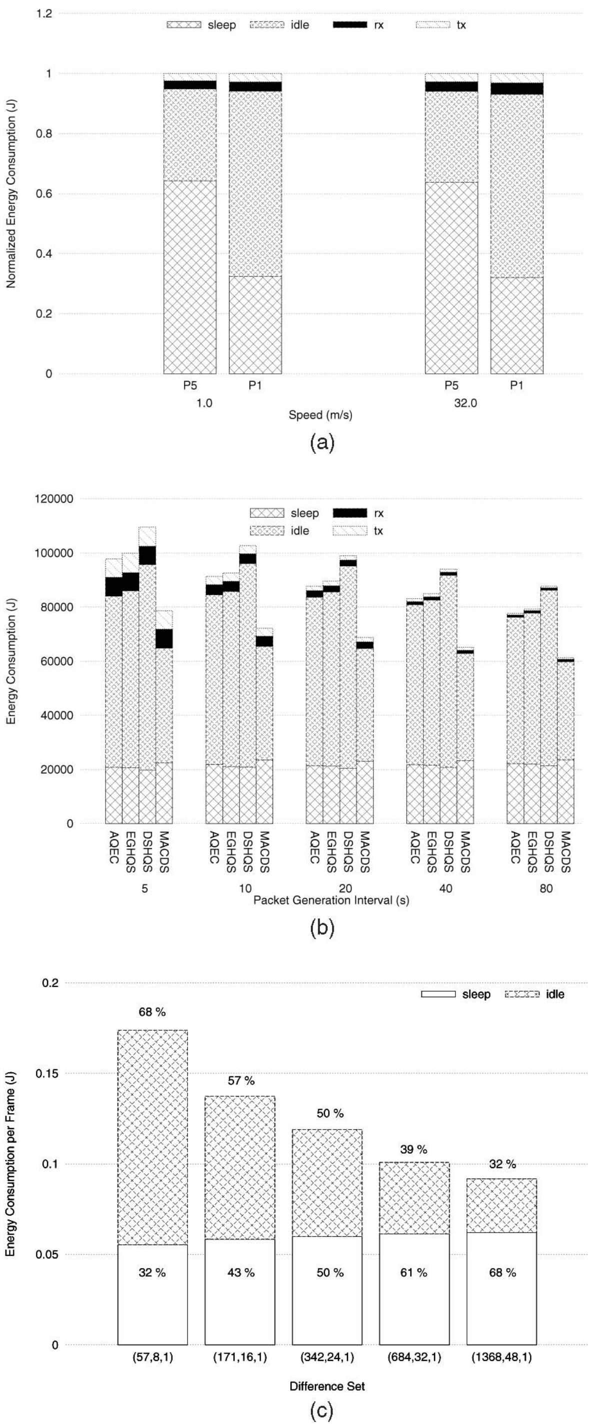

Fig. 11. Breakdown of energy consumption. (a) Impact of node speed. (b) Impact of traffic load. (c) Effect of power consumption model ($P_{sleep}/P_{idle} = 0.078$).

mode. Furthermore, the advantage of the proposed protocols becomes more evident in scenarios using lower sleep power consumption ratios. In addition, multiple PSLs of the proposed protocols are easily applicable to other application scenarios with different network characteristics, such as traffic loads and transmission range, etc. As part of the on-going work, we are investigating how to incorporate energy efficiency into various DTN routing protocols. We will also develop a more deterministic method to construct rotational groups.

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