Power Saving Trade-offs in Delay/Disruptive Tolerant Networks

Oscar Trullols-Cruces, Julian Morillo-Pozo, Jose M. Barcelo-Ordinas, Jorge Garcia-Vidal
Computer Architecture Department, Universitat Politècnica de Catalunya (UPC)
Barcelona, Spain
Email: <trullols,jmorillo,joseb,jorge>@ac.upc.edu

***Abstract*—Wireless nodes such as smart-phones in which the WiFi wireless card is continuously on, consume battery energy in just a few hours. Moreover, in many scenarios, an always-on wireless card is useless because there is often no need for transmission and/or reception. This fact is exacerbated in Delay/Disruptive Tolerant Network (DTN) environments, in which nodes exchange Delay Tolerant Objects (DTO) when they meet. Power Saving Management (PSM) techniques enable the lifetime of the nodes to be extended. This paper analyses the trade-offs that appear when wireless nodes periodically turn off the wireless card in order to save battery in DTN environments. The paper shows the conditions in which a node can switch off the battery without impacting the peer-to-peer contact probability, and those in which this contact probability is decreased. For example, it is shown that node lifetime can be doubled while keeping the peer-to-peer contact probability equal to one. But, further increase of the node lifetime quickly decreases peer-to-peer contact probability. Finally, the impact of power savings in DTO dissemination time is also analyzed.**

***Keywords*-Oportunistic networks, Delay Tolerant Networks, Power saving.**

I. Introduction

Disruption Tolerant Networking (DTNs), [1], are wireless mobile networks that use intermittently available links to communicate opportunistically, using a store-carry-and-forward paradigm. DTNs are particularly useful in sparse environments where the density of nodes is insufficient to support direct end-to-end communication. The main performance metrics of a DTN are deliverability and delay, which are critically dependent on the node mobility patterns that drive the frequency, duration and sequence of contact opportunities. Moreover, DTN nodes are usually untethered devices with limited energy supplies, thus making energy consumption a primary concern, in particular the energy consumed in searching for other nodes to communicate with.

In a mobile DTN, two nodes communicate with each other during the *contacts* that occur when both nodes, either mobile or stationary, are within the radio range of one another. On the other hand, the wireless interface is one of the largest energy consumers in mobile devices, whether they are actively communicating or just listening [2], which means that there is a clear trade-off between saving energy and providing connectivity through opportunistic encounters.

In this paper, the energy saving trade-offs in a DTN (e.g., users with smart-phones) as a function of the *searching* and *sleeping intervals* and as a function of the *node contact duration* is modeled and discussed. First, the peer-to-peer node contact probability is calculated. This contact probability represents the probability that two nodes that meet have the wireless interface enabled, and thus can exchange data. We then derive those operating regions in which the nodes can save energy while keeping maximum contact probability. Furthermore, the impact of peer-to-peer contact probability in the time taken to disseminate a Delay Tolerant Object (DTO) is analyzed.

The paper is structured as follows: Section II reviews the related work. Section III defines the network model while Section IV derives the peer-to-peer contact probabilities and discuss the trade-offs in power saving in a DTN node. Section V aims to validate the mathematical model. Section VI analyses the impact of the peer-to-peer contact probabilities in the time taken to disseminate delay tolerant data and discusses power savings versus delivery times. Finally, Section VII deals with the conclusions.

II. Related Work

Peers in a mobile network alternate between two basic operations: *neighbor discovery* and the *opportunistic transfer of data*. In DTNs, the latter operation has received much attention as part of routing protocols. However, in a sparse DTN network, searching for other nodes consumes a large percentage of time in comparison to data transfer. Consequently, searching for other nodes becomes the dominant drain on the energy of a battery-powered DTN node. For instance, [3] shows that in some scenarios the use of a 802.11 radio to search for contacts in a DTN requires more than 90% of the total energy simply to find other nodes with which to exchange data.

Previous works have addressed mobile system power management by using 802.11 radios for data transfers and *low-power*, *short-range* radios (e.g., 802.15.4, Bluetooth, or CC1000) for neighbor discovery tasks. This idea of using low-power short-range radios (e.g., CC1000) for neighbor discovery is analyzed in [4]. The authors conclude that the addition of a further low power radio introduces a negligible improvement in sparsely mobile DTNs. Via simulation, these authors compare the use of two radios - a low-power radio for discovering contacts and a high-power radio for transmitting data - against a Power Saving Management (PSM) with only a high-power radio. However, the PSM mechanism assumes clock synchronization via GPS. The reason for this is that beacon windows need to be synchronized to start in common discrete intervals. While this solution is appropriate for dense mobile networks, works other than [4], [5] confirm through analytical results that a second short-range radio is indeed inefficient for sparsely populated DTNs. This is because short-range radios miss too many connection opportunities. In this paper we consider a sparse DTN model, and thus focus on a single-radio system.

The use of stationary battery-powered nodes, called throw-boxes, enhances the capacity of DTNs. Banerjee et al, [6], show that without efficient power management, throw-boxes are minimally effective. The authors present a duty-cycled controller for long range radios that predicts when and for how long the mobile node will be in range of the contact duration with the throw-box. The model again needs to beacon position, speed and direction (e.g., using GPS) in order to feed the prediction algorithm. The proposal is tested in the UMass DieselNet Testbed which consists of vehicular mobile nodes. These proposals need GPS data in order to predict contact opportunities or to obtain clock synchronization. In a vehicular network, this assumption does not impose a restriction. But mobile networks consisting of smart-phone users entering closed areas will loose GPS coverage. Moreover, the power consumed in obtaining GPS data is not included in the models.

Finally, Wang et al, [7], investigate the trade-off between the probability of missing a contact and the contact probability frequency in bluetooth devices. This work shows that in bluetooth devices the device discovery process consume as much energy as making a phone call and thus achieves the objective of saving energy using adaptive probing mechanisms. Therefore, in their scheme, bluetooth nodes do not switch off the card and save energy by optimizing discovery frequencies. In our case, we consider WiFi cards in smart-phones that switch the wireless card on and off to save battery, and study the trade-off involved in disabling the wireless card with the contact probability.

III. Network Model

Let us assume a network with N wireless mobile nodes and a set of throw-boxes sparsely distributed over a given area. The throw-boxes are back-boned and thus may be considered as a single node (i.e., a node visiting a specific throw-box has access to any data accessible via any other throw-boxes); see Figure 1. This model is motivated by our study of a Disruptive Tolerant Campus Network, which creates a messaging system between students and staff, using smart-phones or other mobile devices, and fixed nodes (throw-boxes) which are connected to the Fixed Network.

A Delay Tolerant Object (DTO) is a set of packets that are disseminated over the area. If nodes u and v meet, u and v get those new DTOs that they do not share. We assume that the contact duration between nodes is much longer than the time to exchange a DTO.

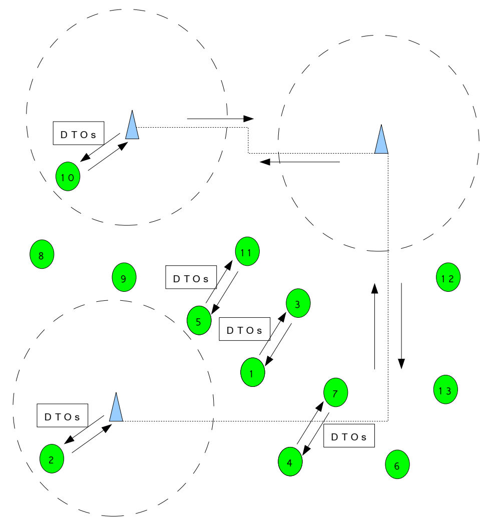


Figure 1. Network architecture: DTOs are disseminated via throw-boxes or opportunistically at contact between nodes.

We use the IEEE 802.11 standard in IBSS/Ad-hoc mode as communication technology. The power consumption of IEEE 802.11 cards have been measured in several papers [8], giving for an ORINOCO PC Gold wireless card the following power consumption figures for the different states: {sleeping, idling, receiving, transmission}={60, 805, 950, 1400} mW. Our own measurements on smart-phone devices give results which are in line with the above.

Instead of using the standard procedure for power saving in IBSS/Ad-Hoc mode, which is not supported by most of the devices, we define a Power Saving Management (PSM) mode as follows: Specifically, a node transmitting or receiving a DTO is in the *transmitting or receiving state*. When the node finishes any of these actions, it switches to a PSM mode. The PSM mode consists of switching between two wireless interface states; see Figure 2:

i) *sleeping state*: a node that is not transmitting or receiving packets, and thus remains in the *sleeping state* during an interval of time equal to T_{sleep}.

ii) *search state*: a node is in the *idle state* during an interval of time equal to T_{srch}. While the node is in the *idle state*, the node switches periodically (i.e, beacon interval T_{bc}) to the *transmitting state* in order to send a beacon and then returns to the *idle state*.

We first note that two nodes would need clock synchronization in order to discover each other if they switched off to the sleeping state after sending their beacons. When a node discovers another node (i.e., listens to its beacons), it initiates a contact exchange as explained in epidemic routing, [9]. We secondly note that T=T_{sleep}+T_{srch} and thus the duty-cycle will be of $\frac{T_{srch}}{T}$.

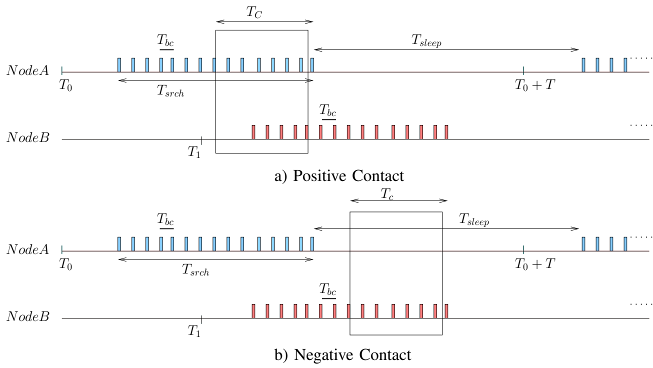


Figure 2. Contact between two nodes with Power Saving Management based on Search/Sleep duty cycling. A node switches on the wifi card at the beginning of the T_{srch} interval. A contact with other node starts at the beginning of T_C interval.

In order to define scenarios for power saving management analysis, we take the example of Nexus One[1] smart-phone with a battery of 1400 mAh and 3.7V that has approximately 250 hours (3G) of stand-by time if the wireless card is off and around 6 hours and a half of lifetime with the wireless card always on. We do not take into account other use of the mobile phone (e.g., phone calls, video, gaming, etc). Four scenarios will be taken as baseline examples:

- **SCEN-0:** The smart-phone has the wireless card on all the time. The smart-phone lifetime, following brochure specifications, will be approximately 6 hours and a half.
- **SCEN-1:** The smart-phone switches the wireless card on in such a way that the duty-cycle $\frac{T_{srch}}{T} = \frac{1}{3}$. The smart-phone lifetime will be approximately 18 hours.
- **SCEN-2:** The smart-phone switches the wireless card on in such a way that the duty-cycle $\frac{T_{srch}}{T} = \frac{1}{6}$. The smart-phone lifetime will be approximately 34 hours.
- **SCEN-3:** The smart-phone switches the wireless card on in such a way that the duty-cycle $\frac{T_{srch}}{T} = \frac{1}{9}$. The smart-phone lifetime will be approximately 50 hours.

IV. CONTACT PROBABILITY

Two nodes that meet and are in the search state have a *positive contact*, Figure 2.a), while if they meet and one of them is in the sleep mode, they have a *negative contact*. For example, Figure 2.b) represents a scenario in which the nodes meet later than in Figure 2.a) as represented by the rectangular areas. Let T_A and T_B be random variables indicating the time at which mobile nodes A and B switch on from the sleeping state to the search state. T_A and T_B are independent and uniformly distributed with probability density function $f_T(t)$=1/T for $0 \leq t \leq T$. Let T_{ctc} be a random variable indicating the time at which a contact would begin if the wifi cards would always be on and let T_c be the duration of the contact. In sparse networks in which the contact rates are low, the inter-contact time is higher than the period T. Thus, when a contact occurs, T_{ctc} is uniformly distributed over the period T and also independent of random variables T_A and T_B. Let us define P_c (contact probability) as the probability that two nodes are in the search state during a contact interval T_c. We consider the following cases:

A. Contact Probability between a mobile node and the infrastructure

When the throw-box is not in the transmit/receive state, it will be in the search state looking for mobile nodes that opportunistically contact the throw-box. The simplest case is when $T_c \geq T_{sleep}$, in which the mobile node will have a contact with probability $P_{c_1} = 1$. The case in which $T_c < T_{sleep}$, the contact probability P_{c_1} will depend on whether the mobile node is in the search mode during the contact interval: $P_{c_1} = Pr\{(0 \leq T_A \leq T), (T_A - T_c \leq T_{ctc} \leq T_A + T_{srch})\}$:

$$P_{c_1} = \int_0^T \frac{1}{T} dt \int_{t-T_c}^{t+T_{srch}} \frac{1}{T} d\tau = \frac{T_{srch} + T_c}{T} \quad (1)$$

Table I summarizes the contact probability for the different situations between mobile nodes and throw-boxes.

Table I
SUMMARY OF CONTACT PROBABILITY, P_{c_1}, BETWEEN MOBILE NODES AND THROW-BOXES.

$P_{c_1} = \frac{T_{srch}+T_c}{T}$	$T_c < T_{sleep}$
$P_{c_1} = 1$	$T_c \geq T_{sleep}$

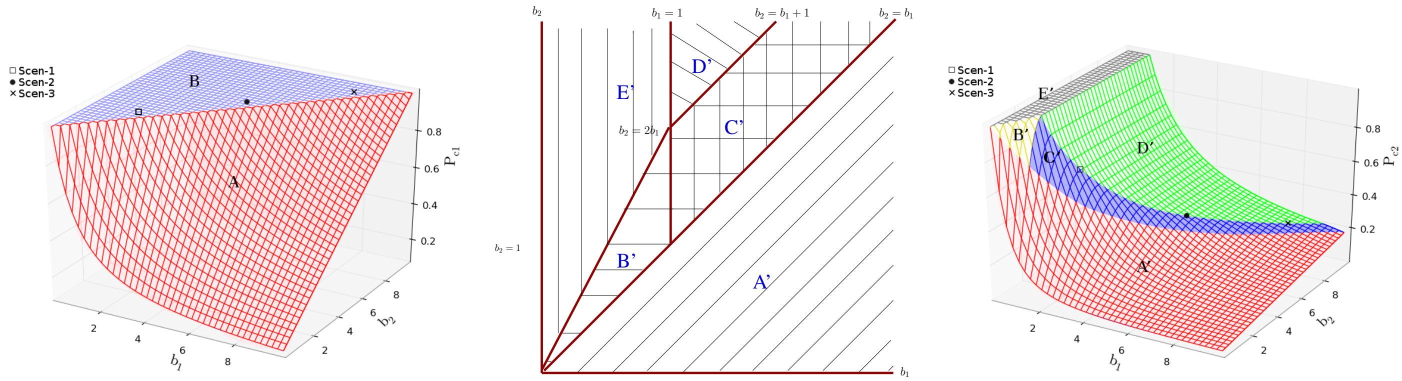
B. Contact Probability between two mobile nodes

There will be a set of different possibilities for calculating the contact probability, P_{c_2}, depending on the lengths of the sleeping state, T_{sleep}, the search state, T_{srch}, and the contact duration, T_c. There are five possible cases, which are summarized in Table II. Appendix A describes how to obtain the different cases.

Table II
SUMMARY OF CONTACT PROBABILITY, P_{c_2}, BETWEEN MOBILE NODES AS A FUNCTION OF PARAMETERS T_{srch}, T_{sleep} AND T_c.

$P_{c_2} = \frac{(T_{srch}+T_c)^2 - T_c^2}{T^2}$	$T_c \leq T_{sleep}$
$P_{c_2} = 1 - \frac{(T_c - 2T_{sleep})^2}{T^2}$	$T_{sleep} \leq T_c \leq 2T_{sleep}$ and $T_{sleep} \leq T_{srch}$
$P_{c_2} = \frac{(T_{srch}+T_c)^2 - (T_c - T_{sleep})^2 - T_c^2}{T^2}$	$T_{srch} \leq T_{sleep} \leq T_c \leq T$
$P_{c_2} = \frac{2T_{srch}}{T}$	$T \leq T_c$ and $T_{srch} \leq T_{sleep}$
$P_{c_2} = 1$	$2T_{sleep} \leq T_c$ and $T_{sleep} \leq T_{srch}$

[1]http://www.google.com/phone/static/en_US-nexusone_tech_specs.html



(a) (b) (c)

Figure 3. (a) Contact probability, P_{c_1}, between mobile nodes and throw-boxes, (b) Contact areas between two mobile nodes, and (c) Contact probability, P_{c_2}, between mobile nodes.

C. Trade-offs between contact probability and power saving

Let us define the following parameters that describe the aggressiveness of the different states: $b_1 = \frac{T_{sleep}}{T_{srch}}$ and $b_2 = \frac{T_c}{T_{srch}}$. Note that $T = T_{srch} + T_{sleep} = T_{srch}(1 + b_1)$. Thus, the duty-cycle $\frac{T_{srch}}{T} = \frac{1}{1+b_1}$ and parameter b_1 is related to how much battery the node will save. Let us assume that a mobile node with the wireless interface always on has a lifetime of L_t seconds. A power saving in which the node performs a duty-cycle of $\frac{T_{srch}}{T}$, the node would increase its lifetime by:

$$L_{dt} = \frac{T}{T_{srch}} L_t = (b_1 + 1)L_t \tag{2}$$

As equation (2) shows, the lifetime increment ΔL_t is proportional to parameter b_1 (i.e., $\Delta L_t = L_t - L_{dt} = b_1 L_t$). Thus, $b_1 = 0$ means that the node always has the wireless interface on, while $b_1 = \infty$ means that the node always has the wireless interface off. Large values of b_2 mean that the contact interval is larger than the search interval, while values of $b_2 < 1$ mean that the contact interval is lower than the search interval. Parameters b_1 and b_2 allow us to analyze the impact of T_{srch}, T_{sleep} and T_c without specifying absolute values for these time intervals. Tables III and IV summarize contact probabilities P_{c_1} and P_{c_2}, respectively, as a function of b_1 and b_2. Finally, Figure 3(b) shows the different regions for contacts between two mobile nodes depending on parameters b_1 and b_2.

Table III
SUMMARY OF CONTACT PROBABILITY, P_{c_1}, BETWEEN MOBILE NODES AND THROW-BOX.

Region	Contact Probability	Intervals
A	$P_{c_1} = \frac{1+b_2}{1+b_1}$	$b_2 < b_1$
B	$P_{c_1} = 1$	$b_2 \geq b_1$

Let us begin by representing P_{c_1} graphically. Figure 3(a) depicts the two regions identified in Table III and shows that

Table IV
SUMMARY OF CONTACT PROBABILITY, P_{c_2}, BETWEEN MOBILE NODES.

Region	Contact Probability	Intervals
A'	$P_{c_2} = \frac{1+2b_2}{(1+b_1)^2}$	$b_2 \leq b_1$
B'	$P_{c_2} = 1 - \frac{(b_2-2b_1)^2}{(1+b_1)^2}$	$b_1 \leq b_2 \leq 2b_1$ and $b_1 \leq 1$
C'	$P_{c_2} = \frac{(1+b_2)^2-(b_2-b_1)^2-b_2^2}{(1+b_1)^2}$	$1 \leq b_1 \leq b_2 \leq 1 + b_1$
D'	$P_{c_2} = \frac{2}{(1+b_1)}$	$1 + b_1 \leq b_2$ and $1 \leq b_1$
E'	$P_{c_2} = 1$	$2b_1 \leq b_2$ and $b_1 \leq 1$

if $b_2 \geq b_1$ it does not matter what the size of T_{srch} is: in this case, one would choose the minimum possible T_{srch} (i.e. the beacon interval) in order to save as much energy as possible, while keeping the maximum contact probability, since immediately after switching on the wireless card the node will detect the throw-box. Note, however, that the optimal operation points are those on the straight line that divides the two regions (i.e. $b_1 = b_2$), because they correspond to the maximum b_1 (maximum energy saving) allowed while keeping $P_{c_1} = 1$. On the other hand, if $b_2 < b_1$, the system will inevitably suffer from lost contacts. This effect can be minimized when b_2 approaches b_1. Asymptotically, making T_{srch} very large would allow this objective to be reached because both b_1 and b_2 would tend to 0. Note, however, that this is not a practical approach since it would imply a large waste of energy. The system must decrease b_1 by decreasing its T_{sleep} as near as possible to T_c to move to the operating region with $P_{c_1} = 1$. So an inherent trade-off exists between contact probability and energy saving.

Let us now turn our attention to Figure 3(c), which represents P_{c_2} as defined in Table IV. The 5 regions of operation can be identified as depicted in Figure 3(b). Region A' is the worst in terms of contact probability. In this region, for a target b_1, low values of b_2 yield low contact probabilities. For a given duration contact T_c, an increase of b_2 implies a decrease in T_{srch}. However, this step would move (increase) b_1 to a new point with lower P_{c_2}. Thus, in order to keep the same P_{c_2}, T_{sleep} should be proportionally decreased. The best contact probability is achieved when b_2 approaches b_1, or in other words, when T_{sleep} approaches T_c. In this case, the contact probability P_{c_2} will be that between A' and B' and C' frontiers. In order to increase b_1, and thus save more batteries, T_{srch} must decrease or T_{sleep} must increase at the cost of decreasing P_{c_2}. The reason for this behavior is quite evident: T_{sleep} is larger than T_c and the larger T_{sleep} becomes, the larger the probability of missing more contacts.

Two regions that represent higher values of P_{c_2} are B' and C'. B' presents the problem that $b_1 \leq 1$ which implies that the sleep period must be shorter than the search period (thus limiting the achievable energy savings), so it is a region completely without interest: the same energy savings can be achieved at region E' but with $P_{c_2} = 1$. So a node operating in this region should increase b_2 (i.e. reduce T_{srch}) while keeping b_1 (i.e. reducing T_{sleep} accordingly), in order to move to operating region E'. Note also that $b_1 = 1$ is the best option in terms of P_{c_2}: the combination of both strategies will conduct the system to an operating point with $P_{c_2} = 1$, which is the intersection between regions B', C', D' and E' and corresponds to $b_1 = 1$ and $b_2 = 2$ (i.e., $T = T_c$ and $T_{srch} = T_{sleep} = T_c/2$). At this point, $P_{c_2} = 1$, while $b_1 = 1$, which implies a duty-cycle of 1/2: duplicates the lifetime when compared with a card always on. If a node wants to increase more its lifetime, he has to decrease its duty-cycle in such a way that $b_1 > 1$. That means moving its operating point to regions A', C' or D'.

Note that ($b_1 = 1$, $b_2 = 2$) is not the only point that allows for $P_{c_2} = 1$: the whole frontier between regions D' and E' allows for that, but between all the points in the frontier, this is the one with lower b_2 (i.e. higher T_{srch} for a fixed T_c). Increasing b_2 would imply decreasing T_{srch}; but in order to keep b_1 fixed at one, $T_{sleep} = T_{srch}$. The result implies switching the wireless card on/off many times. This is important from a practical point of view, because the process of switching a wireless card on/off is energy - and time - consuming, so a system with larger T is more desirable. Operating in other points of region E' implies that $b_1 \leq 1$ and thus less battery is saved without any gain in P_{c_2}. Moving out from region E', region D' is the more favorable case from the contact probability point of view for two reasons: it allows for relatively high values of P_{c_2} while introducing higher energy savings. Note that for a given b_1, P_{c_2} remains constant for any b_2. This implies that by keeping the ratio $\frac{T_{sleep}}{T_{srch}} = b_1 > 1$, T_{srch} is limited by T_c (i.e. $1+b_1 \leq b_2$ implies $T \leq T_c$ and $T_{srch} \leq T_c/(1+b_1)$).

This section can be summarized with the following conclusions: given that nodes have a percentage of contact with duration higher than a certain value T_c, then, designing an on/off period with values $T_{srch} = T_{sleep} = T_c/2$ assures a battery saving of around 50%, since nodes would have these percentage of contacts operating over the frontier E'-D'. The remaining contacts would occur with a probability according to the region in which they take place. Higher battery savings may be obtained if $T \leq T_c$ and $T_{srch} \leq T_{sleep}$ (region D') at the cost of reducing peer-to-peer contact probabilities. Regions A' and C' also allow energy savings, but with worse contact probabilities.

V. Model Validation

We considered using real mobility traces or contact logs as inputs for simulating the previous analysis. For example [10], [11] are trace based studies freely available for download and use. However, this choice was discarded because of the large granularity they used for the traces: the node starts a device discovery at each time step and logs the nodes under coverage. As it will be shown later, assuming a wireless range of 100m, 20% of the contact durations take less than 30s. So, any log with a higher granularity may miss some of the contacts. If we change the wireless range to the approximately 10m of bluetooth, the amount of contacts that may be missed while using such granularity can be really meaningful for our study. Granularity also affects to the observed contact duration. A contact will last a discrete number of time-steps while these can be one order of magnitude longer than the real duration. In [10], the bluetooth antennas of iMotes are used to log contacts with a granularity of 120s, while [11] uses bluetooth antennas of mobile phones to log contacts with a granularity of 300s, while we observed a meaningful amount of contact durations that were shorter than 30s. Unless power limitations are solved, with low power consumption antennas, or higher capacity batteries, thus allowing devices always to remain on, real test-beds cannot be improved to log accurately all the contacts among nodes with finer granularity. These facts encouraged us to use a mobility simulator in order to validate the mathematical model.

In order to evaluate the model, let us consider a urban scenario where pedestrian nodes equipped with wireless devices switch between the sleeping state and the search state with the given durations T_{sleep}, T_{srch}. Our aim is to compare the contact ratio obtained in the simulations with the results obtained from the formulas. The pedestrian mobility traces employed were obtained with the UDel Models [12]. The UDel Mobility Model considers both micro and macro mobility, and is based on (i) real surveys collecting detailed information about how people spend their time, (ii) a task model that focuses on the mobility of people inside buildings, and (iii) an agent model that determines how mobile nodes interact with each other (e.g., each node has a day-long realistic behavior where they wake-up, go to work, have lunch, etc., while avoiding collisions and overtaking slower pedestrians, or waiting at traffic lights). The scenario used is $Chicago9Blk$, included in the default UDel Models Data Set. It consists of a city segment of 400x400m, similar to a Manhattan city model of 4 by 4 streets, where 100 pedestrian nodes spend 12 hours, starting at 8.00AM. Any other vehicular, UAV or static node are not considered. 20 instances of this scenario are obtained using different initial random seeds with the default Udel Mobility Parameters for the pause time, speed, lane-changing, distance-speed relationship, etc.

To avoid any kind of synchronization among nodes, the simulator initializes the nodes, giving a random start over the period T for each node. Then, the mobility traces are used to obtain the coordinates of each node. The simulator considers the position and the $sleeping/search$ state of the nodes in order to log the positive contacts. For the scenario $Chicago9Blk$, we have obtained a contact rate, β, between mobile nodes equal to 0.0071 contacts/s. We note that the positive contact rate between mobile nodes will be equal to $\beta' = P_{c_2}\beta$. The two first steps consist of obtaining the CDF of the contact duration and validating the Peer-to-peer Contact probability, P_{c_2}, shown in Figure 3(c).

The CDF of the contact duration is shown in Figure 4. One may observe how approximately 70% of the contacts have contact durations lasting less than 500 seconds, while the other 30% of the contacts have contact durations in excess of 500 seconds. Figure 4 also zooms contact durations of less than 500 seconds. One may observe that only 20% last less than 30 seconds, and only 30% of the contacts have contact durations less than one minute. These values provide us with a hint about the amount of time nodes could fix b_1 and b_2 and will be used in the next section.

In order to validate the peer-to-peer contact probability, P_{c_2}, Figure 5 shows the simulated results against the contact probabilities as obtained in Table IV and Figure 3(c). For the sake of clarity, instead of comparing the 3D plots, cross sections for several b_1 values are drawn as a function of b_2. The simulated values are obtained with a confidence interval of 99%. As it can be observed, the simulations perfectly match the analytical values.

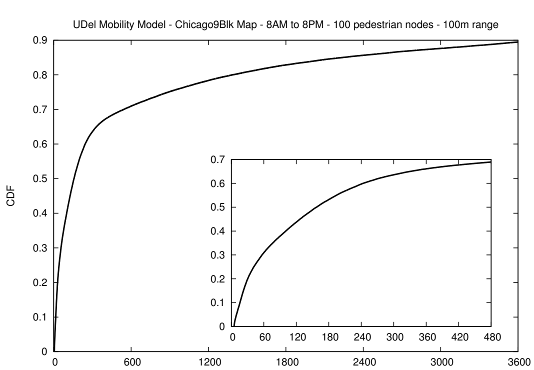


Figure 4. CDF of the contact duration

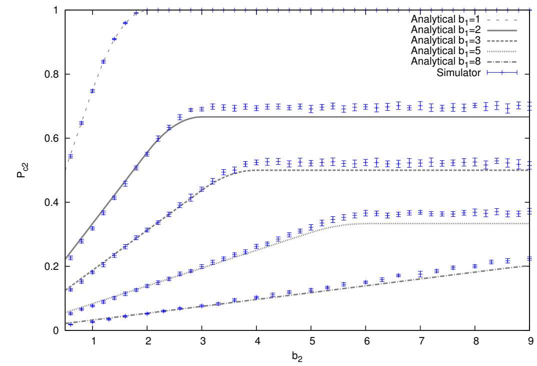


Figure 5. Contact probability, P_{c_2}, between mobile nodes analytical values against simulated ones with a confidence interval of 99%.

Figure 6 shows the peer-to-peer contact probability, P_{c_2}, as a function of T_{sleep} for different values of $T_{srch} = \{5, 30, 60, 120\}$ seconds, obtained with the simulator. Two main points can be observed: the first one is that for a fixed T_{srch}, increasing T_{sleep} implies a low duty cycle and the peer-to-peer contact probability decreases very fast. The second fact is that for the same ratio $b_1 = T_{sleep}/T_{srch}$ (e.g., see the points marked with a box and a circle corresponding to $b_1 = 2$ and $b_1 = 3$), having longer T_{srch} periods imply lower peer-to-peer contact probabilities. Finally, the curves show how the simulation, using a confidence interval of 99% matches the mathematical analysis quite well.

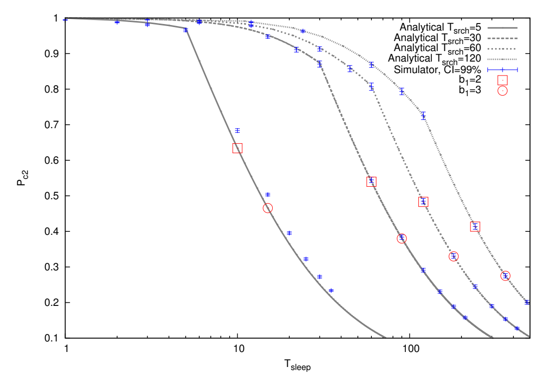


Figure 6. Peer-to-peer contact probability as a function of T_{sleep}

This is further proved in Figure 7, where the contact probability is shown as a function of $T = T_{srch} + T_{sleep}$ for different values of $b_1 = \{0.5, 1, 2\}$. For $b_1 = 0.5$ and 1 both simulations and the mathematical model follow the same line, while for $b_1 = 2$ they conform to the same behavior. However, for small values of T the difference is bigger. The figure shows a slow decay in the contact probability as a function of the total period T. These figures confirm those results obtained in the previous section, where it was shown that in order to have high energy savings the contact probability rapidly decreases.

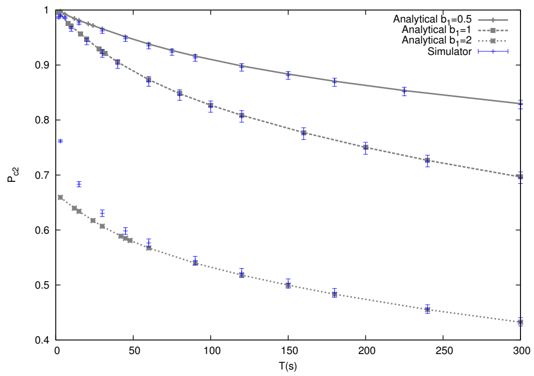


Figure 7. Peer-to-peer contact probability as a function of the period T

VI. Power saving and Dissemination Times

Let us assume that x% of the contacts has contact durations higher than T_C seconds and let us consider a scenario with a duty-cycle $\frac{T_{srch}}{T}$ such that $b_1 > 1$. Then, T_{sleep}=$b_1 T_{srch}$ and $T = (b_1 + 1)T_{srch}$. Since $b_1 > 1$, the region that have better contact probability is region D' with conditions $b_2 \geq 1 + b_1$ (i.e., $T \leq T_C$) and $b_1 \geq 1$ (i.e., $T_{srch} \leq T_{sleep}$). Thus, fixing $T_{srch} = T_c/(1 + b_1)$ assures that x% of the contacts have contact probability $P_{c_2} = \frac{2}{(1+b_1)}$. It is important to stress that T_C is not controlled, it is to say, those contacts that have a duration less than the target T_C will lie in operating regions C' and A', yielding lower contact probabilities. However, a good choice of parameters T_{srch} and T_{sleep} will produce that many of the contacts will operate in regions E' or D'.

Table V
Data parameters for Scen-0 to Scen-3 with $T_c \geq 30$s and $\beta = 3.84 \times 10^{-4}$.

Scenario	b_1	b_2	P_{c_1}	P_{c_2}	$\beta \cdot P_{c_2}$ ($\times 10^{-4}$)	T_{srch} (s)	T_{sleep} (s)
Scen-0	0	0	1	1	3.84	∞	0
Scen-1	2	3	1	0.66	2.53	10	20
Scen-2	5	6	1	0.33	1.26	5	25
Scen-3	8	9	1	0.22	0.84	3.33	26.6

For instance, using Figure 4, 80% of the contacts have contact durations higher than 30 seconds. Table V shows the design parameters for the scenarios defined in section III having $T_c \geq 30$s as target.

As an example of use, we will consider the dissemination of a DTO in a closed area and will use epidemic routing with the aim of characterizing the impact of lower contact probabilities in the trade off between power saving and dissemination time. We will use the ODE model defined in [13] and a simple mobility model such as random direction mobility model to show these trade-offs. As it is shown by Klein et al in [14], epidemic analysis using the ODE model of [13] is accurate in the well-mixed scaling law - i.e., in very sparse scenarios. For denser scenarios, a PDE modeling using diffusion is needed, and we leave these denser scenarios for a future analysis.

Let us consider the time origin as the time at which a node creates a DTO, and let $s(t)$ be the proportion of nodes that have a copy of the DTO at time t. The rate at which the fraction of nodes that have received a copy of the DTO changes, [13], is given by the ordinary differential equation (ODE):

$$\begin{aligned} \frac{d}{dt}s(t) &= (P_{c_1}\alpha + P_{c_2}\beta s(t))(1 - s(t)) \\ &= -P_{c_2}\beta s^2(t) + (P_{c_2}\beta - P_{c_1}\alpha)s(t) + P_{c_1}\alpha \end{aligned} \quad (3)$$

where α is the contact rate between a mobile node and the infrastructure, β is the contact rate between mobile nodes, and P_{c_1} and P_{c_2} are the contact probabilities between a node and a throw-box and between mobile nodes when nodes perform power saving management. This type of equation corresponds, [13], to the fluid limit of a Markov model as N increases. Note that eq. (3) is a Riccati ordinary differential equation that can be solved by substituting $s(t) = \frac{1}{P_{c_2}\beta}(\frac{v'(t)}{v(t)})$. Thus, solving eq. (3), the proportion $s(t)$ of nodes that have a copy of the DTO at time t is given by:

$$s(t) = \frac{P_{c_1}\alpha + P_{c_2}\beta s(0) - P_{c_1}\alpha(1 - s(0))e^{-(P_{c_1}\alpha + P_{c_2}\beta)t}}{P_{c_1}\alpha + P_{c_2}\beta s(0) + P_{c_2}\beta(1 - s(0))e^{-(P_{c_1}\alpha + P_{c_2}\beta)t}} \quad (4)$$

where $s(0)$=$\frac{1}{N}$ is the initial proportion of nodes with a DTO copy Letting α=0, eq.(4) gives us the proportion of nodes using power saving that receive the DTO without infrastructure and letting β=0, eq. (4) gives us the proportion of nodes that receive the DTO only contacting infrastructure.

Let us define the *dissemination time*, T_D as the time needed to disseminate a DTO to a percentage $s(T_D)$ of users. Thus, the dissemination time T_D can be computed from eq. (4) as:

$$T_D = \frac{1}{(P_{c_1}\alpha + P_{c_2}\beta)} ln[\frac{(1 - s(0))(P_{c_1}\alpha + P_{c_2}\beta s(T_D))}{(1 - s(T_D))(P_{c_1}\alpha + P_{c_2}\beta s(0))}] \quad (5)$$

with $s(T_D) \in [\frac{1}{N}, \frac{N-1}{N}]$. Table VI summarizes the dissemination times for the general case (i.e., $\alpha \neq 0$, $\beta \neq 0$) and for the cases in which there is no infrastructure (i.e., $\alpha = 0$, $\beta \neq 0$) and there is only infrastructure (i.e., $\alpha \neq 0$, $\beta = 0$).

Table VI
Summary of dissemination times, T_D, with and without infrastructure.

$T_D = \frac{1}{(P_{c_1}\alpha + P_{c_2}\beta)} ln[\frac{(1-s(0))(P_{c_1}\alpha + P_{c_2}\beta s(T_D))}{(1-s(T_D))(P_{c_1}\alpha + P_{c_2}\beta s(0))}]$	$\alpha \neq 0, \beta \neq 0$
$T_D = \frac{1}{(P_{c_1}\alpha)} ln(\frac{(1-s(0))}{(1-s(T_D))})$	$\alpha \neq 0, \beta = 0$
$T_D = \frac{1}{(P_{c_2}\beta)} ln(\frac{s(T_D)}{(1-s(T_D))} \frac{(1-s(0))}{s(0)})$	$\alpha = 0, \beta \neq 0$

Figure 8 shows the dissemination times needed to reach different percentage $s(T_D)$ of users for several values of α (no infrastructure, and average contact rates of 10^{-3} and 10^{-4} seconds with the infrastructure) and for each scenario. The area is the same as that one used by Klein et al in [14] for a well-mixed scaling law: an area of 16 square Km and N=25 users using random direction with reflection. This scenario has been validated in [14] as representative of a very sparse scenario and is well modeled via ODE analysis. We have chosen a radio range of 100 meters and users move at 1 m/s. The resulting average contact rate is $\beta = 3.84 \times 10^{-4}$. From the figure it is clear that it is extremely costly to reach a high percentage $s(T_D)$ of nodes when there is no infrastructure. This cost is worse in scen-3, with a lower contact probability. As an example, targeting a percentage of users of $s(T_D)$=80%, the dissemination time without infrastructure is approximately of 15 hours in Scen-3, 10 hours in Scen-2, 5 hours in Scen-1 and 3 hours 20 minutes in Scen-0. Adding infrastructure assures that most of the DTOs are obtained when the nodes cross the infrastructure. One may observe that operating in region D' implies that $b_2 \geq b_1 + 1$, and thus, nodes crossing throw-boxes coverage operate in region A (i.e., $P_{c_1} = 1$). For example, the dissemination times decrease to values ranging between 22 to 25 minutes for the four scenarios when $\alpha = 10^{-3}$ (i.e., crossing the infrastructure every 16.6 minutes). Furthermore, since contacts operate in region A with the infrastructure, almost all deliveries are done by the throw-boxes and not by the peer-to-peer contacts.

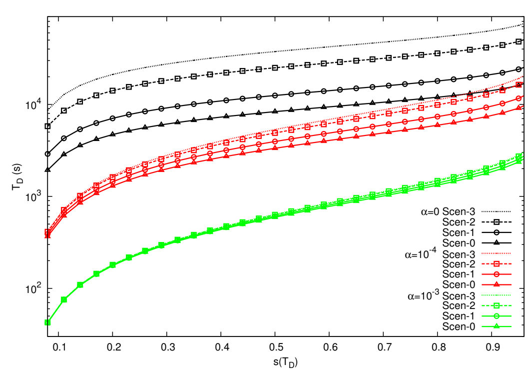


Figure 8. Dissemination time, T_D, as a function of the percentage of users, $s(T_D)$ for the three scenarios. $\beta = 3.84 \times 10^{-4}$ and $N = 25$ users.

Let us now consider the case $\alpha = 0$ - without infrastructure - and calculate how much energy a node spends until a node receives a DTO. We call this parameter *Energy-to-Deliver a DTO*. The *Mean Delivery Delay*, MDD, which is the expected delay between the DTO generation at the source and the delivery to a destination is given by $MDD = \frac{ln(N-1)}{\beta P_{c_2}}$. Scenario 0 with a $b_1 = 0$, $P_{c_2} = 1$ and a $\beta = 3.84 \times 10^{-4}$ has a $MDD = 8.341 \times 10^3$ s. For the reference smart-phone - a Nexus one - with a battery of 1400 mAh and 3.7V, the energy consumed during this time is of $E = 6.673 \times 10^3$ J. With a duty cycle strategy and knowing that the duty cycle is $\frac{T_{on}}{T} = \frac{1}{(1+b_1)}$, the energy consumed for receiving a DTO will be:

$$E = \frac{ln(N-1)}{\beta P_{c_2}}[(\frac{1}{1+b_1})P_{srch} + (\frac{b_1}{1+b_1})P_{sleep}] \quad (6)$$

where P_{srch} and P_{sleep} are the power consumptions in each state. Assuming that for $b_1 \leq 1$ nodes operate in region E' and for $b_1 \geq 1$ nodes operate in region D', the energy consumed for receiving a DTO will be:

$$E = \begin{cases} \frac{ln(N-1)}{\beta(1+b_1)}[P_{srch} + b_1 P_{sleep}] & \text{if } b_1 \leq 1 \quad 2b_1 \leq b_2 \\ \frac{ln(N-1)}{2\beta}[P_{srch} + b_1 P_{sleep}] & \text{if } b_1 \geq 1 \quad 1 + b_1 \leq b_2. \end{cases} \quad (7)$$

Figure 9 shows the trade off between the energy needed to receive a DTO and the duty cycle $\frac{T_{on}}{T} = \frac{1}{(1+b_1)}$. From the figure, it can be observed that there are two zones: the first zone corresponding to $b_1 \leq 1$ - duty cycles between 1 and 0.5 - is the result of $P_{c_2} = 1$. Since the MDD is constant in this interval, the optimal strategy is to have a duty cycle of 0.5 (i.e., $b_1 = 1$) with a minimum average energy consumption of $\frac{ln(N-1)}{2\beta}[P_{srch} + P_{sleep}]$. The second region corresponds to lower duty cycles (i.e., higher b_1). However, since $P_{c_2} < 1$, MDD will be higher and more on/off periods will be needed in order to obtain the DTO. Designing very low duty cycle strategies is impractical since the MDD is too high and the average energy consumption to obtain a DTO will increase due to the number of on/off periods needed to reach this MDD time.

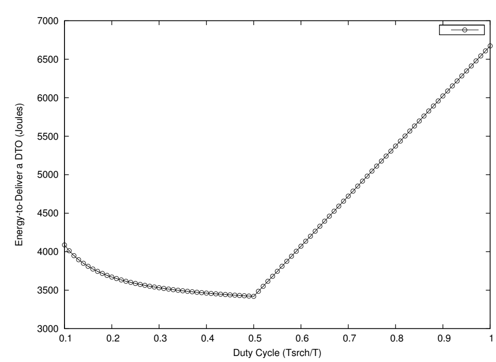


Figure 9. Energy needed to receive a DTO versus the duty cycle.

VII. Conclusions and Future Work

In this paper, power saving trade-offs in DTNs as a function of the searching and sleeping intervals and as a function of node contact duration are investigated. Different operation regions are identified in which a node will have high contact probabilities with both other nodes and/or the infrastructure while allowing energy savings. Simulation results from pedestrian mobility traces show that the mathematical model is accurate and that the contact rates in these kind of networks can be quite low, thereby justifying the need for the nodes to switch off their wireless cards in accordance with the operation regions. We think that the modeling gives a hint on designing strategies to save batteries in this kind of scenarios.

ACKNOWLEDGMENT

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APPENDIX A

In order to calculate the different cases appearing in table II, let us consider the following situations:

- When $T_c \le T_{sleep}$ the contact probability can be calculated as $P_{c_2} = 2 \cdot Pr\{(0 \le T_A \le T), (T_A - T_{srch} \le T_B \le T_A), (T_A - T_c \le T_{ctc} \le T_B + T_{srch})\}$:

$$\begin{aligned} P_{c_2} &= \tfrac{2}{T^3} \cdot \int_0^T dt \int_{t-T_{srch}}^{t} ds \int_{t-T_c}^{s+T_{srch}} d\tau \\ &= \tfrac{(T_{srch}+T_c)^2 - T_c^2}{T^2} \end{aligned} \quad (8)$$

- When $T_{sleep} \le T_c \le 2T_{sleep}$ and $T_{sleep} \le T_{srch}$, the contact probability can be calculated as $P_{c_2} = Pr\{(0 \le T_A \le T), (T_A - T_{srch} \le T_B \le T_A - T_{sleep})\} + Pr\{(0 \le T_A \le T), T_A - (T_c - T_{sleep}) \le T_B \le T_A + (T_c - T_{sleep})\} + 2Pr\{(0 \le T_A \le T), (T_A - T_{sleep} \le T_B \le T_A - (T_c - T_{sleep}), (T_A - T_c \le T_{ctc} \le T_B + T_{srch})\}$:

$$\begin{aligned} P_{c_2} = \; & \tfrac{1}{T^2} \cdot \int_0^T dt \Big[\int_{t-T_{srch}}^{t-T_{sleep}} ds + \int_{t-T_{sleep}}^{t+(T_c-T_{sleep})} ds \Big] \\ & + \tfrac{2}{T^3} \int_0^T dt \int_{t-T_{sleep}}^{t-(T_c-T_{sleep})} ds \int_{t-T_c}^{s+T_{srch}} d\tau \\ & = 1 - \tfrac{(T_c - 2T_{sleep})^2}{T^2} \end{aligned} \quad (9)$$

- When $T_{srch} \le T_{sleep} \le T_c \le T$, the contact probability can be calculated as $P_{c_2} = 2 \cdot [Pr\{(0 \le T_A \le T), (T_A - T_{srch} \le T_B \le T_A - (T_c - T_{sleep})), (T_A - T_c \le T_{ctc} \le T_B + T_{srch})\} + Pr\{(0 \le T_A \le T), (T_A - (T_c - T_{sleep}) \le T_B \le T_A)\}]$:

$$\begin{aligned} P_{c_2} &= \tfrac{2}{T^3} \cdot \Big[\int_0^T dt \int_{t-T_{srch}}^{t-(T_c-T_{sleep})} ds \int_{t-T_c}^{s+T_{srch}} d\tau \\ &+ \int_0^T dt \int_{t-(T_c-T_{sleep})}^{t} ds \Big] \\ &= \tfrac{(T_{srch}+T_c)^2 + (T_c - T_{sleep})^2 - T_c^2}{T^2} \end{aligned} \quad (10)$$

- When $T \le T_c$ and $T_{srch} \le T_{sleep}$, the contact probability can be calculated as $P_{c_2} = 2 \cdot Pr\{(0 \le T_A \le T), (T_A - T_{srch} \le T_B \le T_A)\}$:

$$P_{c_2} = 2 \cdot \int_0^T \tfrac{1}{T} dt \int_{t-T_{srch}}^{t+T_{srch}} \tfrac{1}{T} ds = \tfrac{2T_{srch}}{T} \quad (11)$$

- Finally, $P_{c_2} = 1$ when $2T_{sleep} \le T_c$ and $T_{sleep} \le T_{srch}$.

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