Achieving Energy-Efficiency with DTN: A Proof-of-Concept and Roadmap Study*

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Abstract. Mobile networking devices autonomy can be prolonged by condensing sporadic traffic at the last hop, allowing the receiver to *sleep* during *idle* intervals. We claim that Delay Tolerant Networking principles are a natural fit for this application and, along with a novel rendezvous mechanism, employ DTN to achieve energy efficiency. The effectiveness of the proposed scheme is supported by select evidence from our previous experimental work. The presented experimental evidence is followed by a detailed discussion on ongoing development work and future research directions.

1 Introduction

Mobile devices capable of connecting to the Internet through a wireless 802.11 LAN have become commonplace, even with non technologically-savvy users. The sophistication of these devices, along with the need to operate longer hours, creates an ever-increasing energy demand, not matched by the advances in battery technology. The networking subsystem of a mobile device has been identified as a major culprit in draining battery power, accounting for up to 60% of the total energy consumption in network intensive applications [1].

The need to save energy had been identified early in the development of 802.11 and, as such, energy saving provisions have become part of the standard [2]. The standard defines a *sleep* state for a Wireless Network Interface Card (WNIC), in which the device maintains its status as a member of the LAN, while energy expenditure remains very low. Switching the WNIC to sleep state in an intelligent manner has been a research focus in the past; it is, however, a novel contribution on our part to employ Delay Tolerant Networking (DTN) ([3], [4]) concepts in order to achieve energy efficiency. The proposed internetworking overlay exploits two major DTN properties: (i) storing packets for as long as it is necessary, regardless of communications disruptions; and (ii) enhancing the edge nodes with the functionality of collecting a sufficient amount of data, prior to transmitting to the end node.

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In this work we present select concepts and results from our past work on the subject ([5], [6]), as well as focus on ongoing work, future goals and promising ideas. Evaluation of the proposed schemes and mechanisms is made possible with the ns-2 network simulator. Energy efficiency is facilitated by a novel rendezvous mechanism, which takes advantage of the traffic shaping capabilities of DTN [6]. At the time of writing, we are in the process of developing a DTN agent for ns-2 that will allow for more sophisticated experimentation, and assist in addressing design and implementation issues beyond a proof-of-concept study. We have also implemented in the simulator a passive bandwidth estimation (BE) mechanism hoping to give greater visibility to the BS and thus allow for more efficient scheduling decisions.

The rest of the paper is organized as follows: In section 2 we present related work focusing on energy conservation, DTN, and bandwidth estimation approaches. In section 3 we present our proposal, as well as the simulation model used in the experiments, while in section 4 we include select experimental results. In section 5 we discuss ongoing work and future research directions and, finally, in section 6 we summarize our conclusions.

2 Related Work

In network intensive applications, a significant portion of the overall energy required for the device operation is consumed by the networking subsystem [1]. In [7] Jones et al. provide a comprehensive survey of specific mechanisms that can be employed in each of the layers in the network protocol stack. The 802.11 protocol [2] provides a mechanism that buffers incoming data at the BS, allowing the mobile devices to switch their WNICs to sleep state in the meantime. The energy conservation potential of this mechanism is limited by the relatively small buffer space at the BS and lack of visibility at higher network layers, leading many researchers into examining alternative methods based on the same core principle. In [8], Adams et el. propose a technique that buffers data at higher network layers, hiding it from the BS. Authors in [9] further develop the proxy idea, introducing a scheduler service at the Base Station and a proxy at the mobile terminal.

Delay/Disruption Tolerant Networking allows for wide-spread store-and-forward strategies that could extend data buffering and traffic shaping beyond the BS. The architecture for DTN was designed initially to facilitate packet-switched data transmission in space communications [3]. The deployment of the DTN Bundle Protocol [4] in space aims at seamless communication between network components on earth and space devices. However, researchers investigate applying DTN on networks with similar characteristics to space networks such as Mobile Ad-hoc Networks [10], Ad-hoc Sensor Networks [11], and highway networks [12]. However, to the best of our knowledge, DTN has not been evaluated as an overlay network for providing energy efficiency. Transmission scheduling at the BS can be greatly improved if bandwidth availability is known to DTN.

Estimating the available bandwidth has been a research focus in the networking community for over two decades; one of the first such efforts was packet pair probing in the early nineties [13]. Bandwidth estimation techniques usually belong to one of two broad categories: active and passive. Active bandwidth estimation techniques inject probing traffic into the network, take certain measurements and use them to calculate available bandwidth. Passive bandwidth estimation in wireless networks take advantage of the broadcast nature of the communication in order to snoop on in-range transmissions and calculate idle periods of the medium. For single-hop, wireless networks such as the 802.11, many researchers suggest that passive methods are more pertinent than active ones ([14], [15], [16]). Generally, passive bandwidth estimation techniques are non-intrusive (i.e. do not burden the network with extra traffic), more responsive (i.e. no probing is required; channel utilization information is readily available), and more accurate than active techniques (i.e. active techniques rely on assumptions that do not hold for wireless 802.11 LANs [16]).

3 Energy-Efficient Internetworking Overlay

Our DTN-based, energy-efficient internetworking overlay takes advantage of the 802.11 feature that allows switching the WNIC to the *sleep* state [2]. While in the sleep state, the energy consumption of a WNIC is at least an order of magnitude less than the consumption in one of the active states (*transmit*, *receive*, *idle*) [17]. The BS buffers data at the last hop of an incoming data transfer, allowing the WNIC of the wireless receiver to be safely switched to the sleep state in the meantime. In this work we assume infinite buffers; postponing study of storage limitation issues for the future.

In order to take advantage of the idle connection intervals created by the buffering at the BS, we proposed a *rendezvous* mechanism between the BS and the wireless receiver [6]. When the buffered data is flushed, the receiver is notified of the next rendezvous time, switches its WNIC to the sleep state and wakes it up again in time to receive the next bunch of data. At every rendezvous the BS calculates the time interval for the next rendezvous, taking into account the incoming data rate of the previous interval and the target buffer occupancy set by the user (detailed explanation and numerical examples can be found in [6]).

3.1 DTN Overlay Simulation Model

The behavior of the bundle protocol was emulated by introducing a proxy application at the BS. The application connects to an input TCP agent, receiving data from the source of the data transfer, and an output TCP agent, transmitting data to the wireless receiver. Energy expenditure calculations were facilitated by modifying the physical layer of the wireless node, so that the state transitions are logged. Post-simulation processing computed energy consumption based on the state transitions and the effect of the rendezvous mechanism.

At post-simulation, the energy expenditure is calculated based on the following parameters: transmit power (txPower), receive power (rxPower), idle power (idlePower), sleep power (sleepPower), transition power (transPower) and transition time (transTime).

Idle intervals are converted to sleep intervals whenever possible. The power figures for the various WNIC states are set as follows [17]: txPower = 1.400 Watts, rxPower = 0.950 Watts, idlePower = 0.805 Watts and sleepPower = 0.060 Watts.

The diagram in Fig. 1 depicts the network topology used in the simulation. Network nodes are named as N1 – N6, with N4 being the BS node and N6 the wireless receiver. Links L13, L23, L34 and L45 are wired, while WL is the wireless link between the BS and the receiver. The data transfer follows the N1→N3→N4→N6 route, while the competing flow, when present, follows the N2→N3→N4→N5 route. The bandwidth and delay values for all the links are as follows: L13 - 2Mb, 100ms, L23 - 3Mb, 100ms, L34 – 300ms delay and varying bandwidth, L45 - 3Mb, 100ms, WL - 802.11 with a data rate of 11Mb and a basic rate of 1Mb. More on the experimental setup can be found in [6].

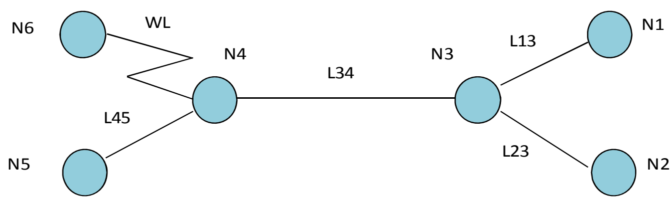

Fig. 1. Network Topology

4 Experimental Results

This section includes select experimental results from our previous work. The results in greater detail can be found in [6]. We present two setups, both of which experiment on an FTP connection when a competing, CBR flow is present. In the first setup the variable is the wired bandwidth, while in the second the variable is the Target Buffer Occupancy (TBO). In both setups there is an *End-to-End* (E2E) scenario, where an end-to-end connection between N1 and N6 is tested, and a *Split* scenario, where the connection uses the splitting application at the BS.

4.1 Varying Bandwidth FTP Transfer

In this set of experiments the backbone link is assigned a constant delay of 300ms, while the bandwidth varies from 0.5Mb to 3.5Mb in steps of 0.5Mb. The transfer duration of the E2E and the Split cases are virtually identical, spanning from around 360 seconds in the 0.5Mb setting to 90 seconds in the 3.5Mb setting.

Fig. 2 shows the energy consumption required at the mobile receiver for each transfer. It can be observed that small bandwidth values of the bottleneck link (leading to high congestion) produce greater energy gains when the Split application is employed. In the highest congestion setting (i.e. 0.5Mb bottleneck bandwidth), use of the Split application achieves approximately 64% energy conservation compared to the E2E case. As the bottleneck link capacity is decreased (network congestion eases) the energy conservation decreases as well, remaining however at significant levels.

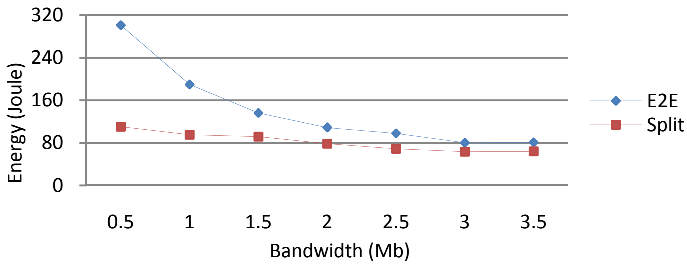

Fig. 2. Varying Bandwidth Energy Expenditure

Fig. 3 presents the state transitions for 10 indicative seconds during the file transfer in both cases, at a backbone bandwidth of 2Mb and with the presence of a competing flow. The Active state at the top includes sending, receiving and idle intervals (not adequately long for switching to sleep state), while the potential sleep state at the bottom includes idle intervals long enough to allow a switch to the sleep state. The chart clearly shows that in the E2E case, the WNIC needs to switch to active more frequently and it usually needs to remain active longer than in the Split case.

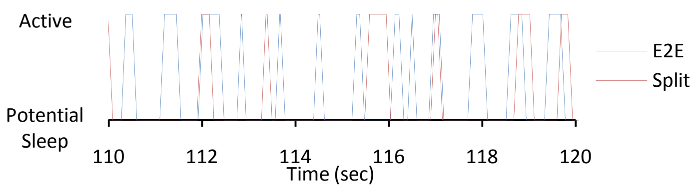

Fig. 3. FTP, 2Mb Bandwidth, Competing Flow State Transitions

4.2 Varying Target Buffer Occupancy FTP Transfer

The experimental setup of this section uses a 300ms delay and a 2Mb bandwidth for the backbone link; a competing flow is present and the TBO is varied from 0 to 180KB. The transfer duration for all TBO values is identical and, therefore, not reported here.

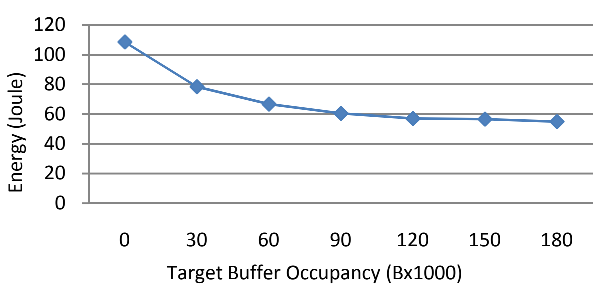

Fig. 4. FTP, Varying Target Buffer, FTP, With and Without a Competing Flow, Energy Consumption

Fig. 4 depicts the energy expenditure for all tested buffering values. As the TBO increases, the energy expenditure drops, reaching a value of around 55 Joule for the 180 Bx1000 case. The wired part of the connection is significantly slower than the last hop, so the wireless LAN is consistently underutilized, allowing for more efficient buffering. Fig. 5 depicts the actual buffer occupancy fluctuations throughout the 60 Bx1000 TBO data transfer. It can be seen that the buffer occupancy goes through two distinct phases during the transfer, bordering at around second 60. At the start of each phase, TCP is in slow start, and the incoming data flow increases sharply so the rendezvous mechanism takes a few seconds to respond. For the rest of the duration of each phase, the buffer occupancy falls within a 40 – 80 Bx1000 range, approximately 33% of the TBO. In a real-world situation where multiple devices receive data in parallel, the aggregate buffer occupancy could be predicted, allowing for efficient buffer planning.

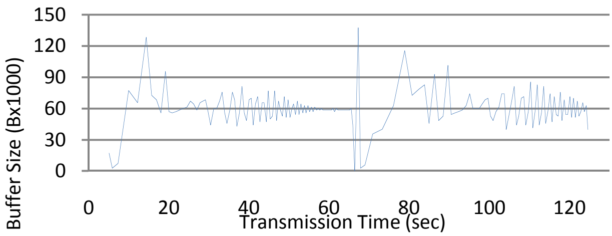

Fig. 5. Actual Buffer Occupancy at 60 Bx1000 Target Buffer Occupancy

5 Model Development and Future Work

5.1 Bandwidth Estimation Model

The motivation for employing bandwidth estimation techniques on the last-hop wireless link was to enable higher network layers exploit bandwidth availability information in order to make data transmission scheduling more efficient. For example, the DTN layer at the BS could dynamically adjust the amount of buffered data based on the available bandwidth. Another possible application of bandwidth estimation is enabling the transport layer to distinguish between congestion related packet drops and wireless error of random nature. The DTN layer at the BS could employ a specialized TCP version that would adjust its transmission strategy according to bandwidth availability information.

Latest trends in estimating bandwidth availability, as described in the related work section, clearly suggest that employing a passive bandwidth estimation method, in favor of an active, probing-based one, would be the most suitable approach in our case. A simple, passive bandwidth estimation mechanism has been implemented in ns-2. The mechanism is fitted into the wireless MAC layer of the BS and records busy periods for the medium, as well as idle periods that are part of the collision avoidance strategy of the 802.11 protocol. Due to the nature of the wireless network and the inability of WNICs to transmit and sense for other transmissions simultaneously, 802.11 employs both a physical and a virtual Carrier Sense mechanism in order to minimize the probability of collisions. Our bandwidth estimation mechanism considers periods of inactivity that are part of the protocol collision avoidance strategy as busy periods. Thus, our algorithm takes into account: reception of segments, transmission of segments, back-off periods, Inter-Frame Spaces (i.e. Short IFS, Distributed IFS, etc.), and transmission deferral due to virtual Carrier Sense (i.e. Network Allocation Vector channel reservations). Details about the 802.11 protocol can be found in [2].

The busy and total duration amounts are stored in the first elements of two arrays and they get updated every time there is a switch in the state of the algorithm (i.e. busy-to-idle, idle-to-busy). A timer is set off at regular intervals and shifts the measurements in both arrays by one position to the right (it resets the first element and discards the last element of both arrays). The number of the time slots in the two arrays, as well as the time interval for the shifting of the values can be set by the user. When higher network layers query for the available bandwidth estimate, recent measurements have a higher contribution to the calculated utilization than measurements that are farther away into the past. Higher layers are passed a pointer to the MAC layer so that cross-layer communication of that sort can be realized. The calculated channel utilization figure is combined with the maximum channel capacity giving the available residual bandwidth.

5.2 DTN Agent Model

The experimental results presented in section 4 show that, in principle, application of DTN in conjunction with the rendezvous mechanism can lead to significant energy conservation in mobile wireless receivers. In order to expand our experimental work we are in the process of developing an ns-2 DTN agent that incorporates both a set of desired DTN-related characteristics, as well as the rendezvous mechanism. At the time of writing, a basic version of the agent has already been implemented, while new functionality is being continuously added.

The DTN agent will be deployed on multiple nodes along the network path (additionally to the BS) and enable studying issues such as: data storage distribution, route selection based on available buffer size, bundle sizing based on delay requirements. Incorporating the rendezvous mechanism into the DTN agent will allow for using the inherent energy model of ns-2, as opposed to the post-simulation calculations currently applied, solidifying the energy expenditure reporting. The DTN agent will also do scheduling in case multiple mobile end-nodes are receiving data at the same time and/or multiple flows are being directed to the same mobile end-node.

Achieving the desired DTN functionality implies that each DTN entity must have multiple incoming and multiple outgoing transport agents. As part of the current design, no routing functionality will be available at the DTN layer, so all routes must ultimately lead to the final destination (this requirement should be met during topology setup). Outgoing agents will be sorted in priority order so that dynamic route selection will be possible. In this original design, route selection will depend only on available storage. Therefore, the DTN entity will select for each incoming bundle the outgoing agent with the highest priority that has available buffer space to store the bundle and, thus, accept custody for it. A DTN agent with a receiving application and no outgoing agents will be considered as the sink node and will notify the application of a received bundle instead of forwarding the bundle downstream. The agent receives data either from the attached application (if any), or from the upstream DTN agent to which it is connected. At the event of receiving a bundle segment, the DTN agent will either immediately forward it to the downstream node (cut-through) or wait for the entire bundle to be received before proceeding.

Storage-based routing assumes that each DTN entity must have knowledge of the buffer space availability of the downstream DTN entities in order for route selection to be possible. Exchange of storage space availability information calls for backward communication between DTN entities. Backward communication is also necessary for acknowledging bundle reception (i.e. accepting custody). Development of the backward communication is underway and can be realized both as a TCP acknowledgment piggy-back as well as a stand-alone DTN control bundle.

The new agent also needs to convey information on the forward path, in order to accommodate both the standard DTN functionality as well as the rendezvous mechanism. The rendezvous mechanism requires that the mobile host is notified about when each chunk of data has finished transmitting, as well as the time until the next rendezvous. Standard DTN as well as the rendezvous-related information is included in a new DTN header, created in ns-2. Among others, the DTN header contains information such as: bundle sequence number, bundle size, segment number, next rendezvous time, available buffer space, and custody acceptance. The DTN header is included in bundles travelling in both directions of a connection.

6 Conclusions

The goal of this paper was two-fold: i) presenting our DTN-based scheme for energy conservation, along with select results of the simulation experiments conducted thus far, ii) reporting on the ongoing work and future directions of our research. The experimental results provide adequate evidence that our proof-of-concept design is capable of enabling energy-efficient communication, without the need to sacrifice data transfer performance. Furthermore, the proposed rendezvous mechanism appears to be an effective, in-band means of communicating idle interval information, allowing the mobile receiver to safely switch its WNIC to sleep mode during periods of inactivity. The experimental results also advocate that the rendezvous mechanism promptly responds to incoming data rate fluctuations, facilitating efficient buffer planning. In the future, the response to fluctuations of incoming traffic can be further improved by utilizing historical data and employing more sophisticated prediction algorithms.

The prototype simulator design, used in the presented experiments, must be extended and encompass functionality necessary for deployment in real-world environments. One such extension is the scheduling capability at the BS. The BS must be able to schedule data transmission from multiple flows destined to the same mobile receiver, as well as from multiple flows destined to multiple receivers in such a way that exploitable idle intervals can still be produced. Scheduling data transmissions at the last hop can also be benefitted by a passive, bandwidth estimation mechanism, a simulation model of which has already been created. The scheduling algorithm must also be able to accommodate real-time traffic, with certain delay limitations. Finally, we need to exploit the inherent DTN capability of distributing buffering storage over the network and, thus, relieve the BS of the pressure for excessive storage requirements. The ns-2 DTN agent that is under development will assist in studying all the above issues.

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