A novel *DTN* based energy neutral transfer scheme for energy harvested WSN Gateways

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ABSTRACT

To overcome the problem of unavailability of grid power in rural India, we explore the possibility of powering WSN Gateways using a bicycle dynamo. The "data mule" bicycle generates its own power to ensure a self sustainable data transfer scheme to benefit small and marginal farmers. In our agricultural scenario, farmers have to generate electricity to get access to the technology. Our power measurements show that it is indeed possible to drive GPRS technologies with this power. We propose *Transfer Energy Budget* - a two way metric for gateway nodes to announce the available energy for relaying data. To achieve our goal, we exploit the DTN stack and introduce necessary modifications to its configuration. The results indicate that a 50 packet buffer has the least transfer energy budget with a data latency of about 31 seconds.

Keywords

ICTs, Agriculture, Bicycle dynamo, DTN, WSNs

1. INTRODUCTION - AGRICULTURE AND THE RURAL CONTEXT

Small and marginal farmers own about $1-4$ hectares of land. They solely depend on rainfall for irrigation. Their lands are generally located at a higher elevation ($2-25\,\text{m}$) compared to the rich farm lands resulting in a high run-off. Farming in Semi-Arid regions is further characterized by low rainfall (500 mm over 6 months). Crop production has been subjected to weather and large scale attack due to pest and diseases. Over 75% of the tillable land in Karnataka state, India, is dependant on rainfall. The state has witnessed rainfall deficiency once every 4.3 [1]. We explored the application of wireless sensor network technologies for the benefit of small and marginal farmers [2]. The key idea is to provide information about the standing crop by evaluating its stress in adverse situations such as drought and pest attacks that impact the yield. The farmers could make informed decisions about investing in purchase of water to save the crop, or spraying a pesticide at the right time. Sometimes, a nutrient supply during a specified period is an important advice to the farmer. The project site chosen was Chennakesavapura (Pavagada Taluk, Tumkur District of Karnataka, India). This heterogeneous distribution has 10 sensors each in 2 clusters. The data collected by the sensors includes soil moisture, temperature, pressure, humidity and rain data. An ad hoc wireless sensor network enables data aggregation at a sink node. Additionally, data relays are required to transfer the data for the purpose of analysis and decision science. Since the village has access to telephone and GPRS technologies, we explored a Wi-Fi cum telephone network in one of the clusters and GPRS technologies in the other cluster as data relays.

Availability of grid power is a major concern across most villages in India. Often power cuts last for 12-16 hours a day. Computers, telephone modems, Wi-Fi access points, and the village telephone exchange all need power. During the monsoon months, lightning strikes have burnt several of the system components including components of supply grid. During some months, the village may not have power for 3 days continuously. GPRS is a promising technology with fewer system components, but requires sufficiently high energy with peak currents of about 1.6A during data transmissions. Even large battery backups are insufficient to guarantee the continuous operation.

Is there a solution to this problem? Can we generate power just sufficient for GPRS transmission? In this paper, our objective is to show that energy to power GPRS can easily be generated in the village and by villagers. We show that the system can become free from grid power and work in a self sustaining mode. We propose and implement a scheme, wherein an alternate source of energy; a power source such as an ordinary bicycle dynamo is sufficient to drive the GPRS system components. Our scheme utilizes a data relay hybrid communication system comprising of Wi-Fi and GPRS technologies. Figure 1 depicts the big picture of our solution. The figure shows that data from the field station sink

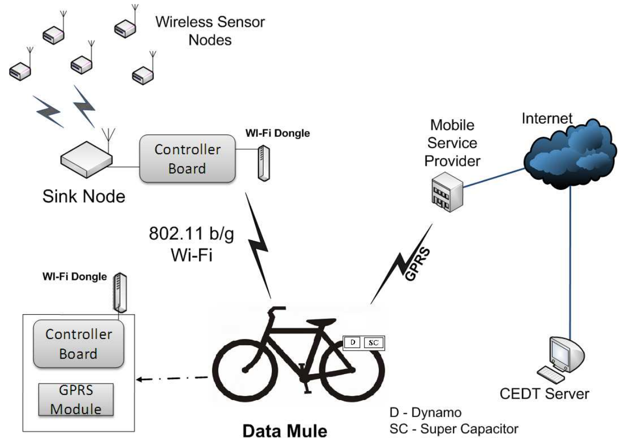


Figure 1: Proposed Scheme Showing data transfer over GPRS .

node is transferred to the bicycle over a Wi-Fi connection and subsequently data relay is over a GPRS link. In this paper, we refer the bicycle system as the "Data mule" since it is expected to visit several clusters to download data from an aggregation point. The system on the bicycle runs out of harvested energy generated by the dynamo. Moreover, as demonstrated in this paper, a battery is not a panacea to all power problems. We show that a supercapacitor is sufficient for our purpose to overcome the limited charge-discharge cycles besides being ecologically friendly.

2. MOTIVATION AND RELATED WORK

Several issues related to power availability and its nexus to reliable data gathering in the field were discussed in [3]. The authors show that data transfer using GPRS technologies has increased long term reliability due to reduced system components compared to other fixed infrastructure technologies. At the same time, we showed high power requirements for GPRS and also the technological pitfalls in terms of packet retransmissions whenever there is an operator preference for voice over GPRS packet data. While we do not solve the problem of power requirements and its availability, we indeed showed that packet buffering improves energy efficiency compared to packet by packet data transfer. In this paper, we adapt packet buffering as against individual packet transmission.

For the purpose of data transfer from the field unit to the data mule, we utilize the Delay/Disruption Tolerant Network (DTN) stack from [14]. The DTN Architecture and other key open issues are discussed by [8]. These issues include connection disruption and heterogeneity. The architecture proposes a collection of protocol-specific convergence layer adapters to provide functionality and carry DTN protocol data units called "Bundles". In this stack, data is converted into user controlled bundles of data. Such bundles are then reliably transferred between two end points using the TCP protocol. Perhaps one important reason for the popularity of the DTN communication stack is its application in remote areas where communication infrastructure is nonexistent or difficult to establish. Several works in the literature show novel ways to improve DTN performance. For example, in [9], a system which implements a mechanism with the goal to minimize packet transfers between entities such as buffers and persistent storage with a goal to accelerate DTN transmissions is proposed. In [10], to solve the problem of message replication in DTNs, authors propose an adaptive optimal buffer management scheme for a limited bandwidth and variable message sizes. Authors use the assistance of global network statuses such as transmission opportunity, inter-meeting time and contact time. In [11], the DTN stack is ported over a commercially available wireless access point. They show the impact of bundle size on throughput and goodput. Several works in the literature also mention about data mules used for improving energy efficiency and efficient data gathering. For instance in [4], through simulations the performance of discovery and data transfer phases is analyzed. In [5] the data mule is used to construct variable length shortcuts. The mules move between nodes that do not have direct wireless communication link adding a simultaneous delay increase and path length reduction component. In [6], the problem of optimal data transfer from sensors to data mules and derive an upper bound for the performance of ARQ-based data-transfer protocols is analyzed. They propose adaptive data transfer technique that significantly reduces the time required by a sensor to transfer its messages. In [7], "data mule scheduling" scheme to minimize data delivery latency is proposed. In summary, most existing works look at performance improvement but do not propose any application towards improvement of *energy efficiency*.

In our work, since agriculture sensor data does not have a strict real time constraint, we employ the DTN stack and exploit its features from the view of energy availability rather than connectivity. We propose an algorithm towards an energy based data transfer where data bundles are exchanged between DTN end points to match the minimum energy available between DTN node pairs without compromising the data reliability. Thus, the energy available is also indirectly converted into discrete bundles with the goal of being energy neutral operation of the data mule carrying the GPRS relay.

3. EXPERIMENTAL SETUP

Since our primary source of energy for the data mule is the dynamo, it becomes important to characterize the source. Since we have done away with batteries, it becomes necessary to dimension the size of the supercapacitor for energy storage. The following subsections show the source characterization and calculation of the value of supercapacitor.

3.1 Characterisation of the energy source

We used an 8 pole dynamo that is rated for a maximum of 3 watts and performed extensive measurements by rotating the dynamo at various speeds to verify the published maximum power capability. Table 1 provides useful insight into the power generated at several cycling speeds. The results were obtained by conducting the Voltage-Current (V-I) characterization of the energy source. The results in Table 1 indicate that it is possible to generate approximately 1.1watts to about 2.9watts for cycle speeds between $11 - 13$ kmph.

Table 1: Generated dynamo power with respect to cycle speed

Cycle speed in kmph	Power generated in watts
13.2	2.9
13.0	2.6
12.5	2.1
11.0	1.1

3.2 Supercapacitor value calculation

Supercapacitors have started becoming popular due to their recent increased energy densities. We used a 120 F capacitor across all our measurements. Since our energy requirement is to the extent of retrieving the data bundles from the field station node and transferring the same over a GPRS link, we do not require an infinite buffer or even an oversized buffer. Based on the energy measurements we conducted, (shown in the next section), we evaluated the capacitance required to transfer one data bundle of 50 packets. The minimum capacitance value required can be evaluated from Eq.(1)

$$C = \frac{2E}{V1^2 - V2^2} \qquad (1)$$

Since the GPRS-Sensor Network bridge works in the voltage range between 5.5 volts ($V1$) and 4.35 volts ($V2$), our calculations show that for transmitting a 50 packet buffer, a super capacitor of 75.14 F is required. The advantage of this optimal value ensures that the cyclist does not have to pedal for longer periods to kick-off packet transmissions. We found that 20 min of cycling at about 13 kmph is required to generate energy sufficient to transfer a 50 packet buffer.

4. RESULTS

In this section we experimentally evaluate the optimal size of the GPRS buffer and for this size, our new metric *Transfer Energy Budget* (TEB) is found to be the least. In another measurement result, we evaluate the packet delivery latency from the time a bundle arrives at the mule to the time it reaches destination server.

4.1 Energy Consumption by GPRS board

We have used a GPRS-Sensor Network bridge from [12]. The hardware comprises of a GPRS module from Siemens (model - TC65) and a sensor network sink node. The sink is based on TI's MSP 430 microcontroller and XE 1205 radio from semtech [13]. For the purpose of this paper, sensors in the field were programmed to send a data packet to the sink node every 20 s. The packet size was fixed at 32 bytes. The sink node, upon the receipt of data packet, forwards it to the buffer of GPRS module. The buffer for holding GPRS data is available both inside the module as well as on an external SD card format flash memory. For our experiments, we have used the internal free 1.7MB memory. The GPRS module, depending on its state, can operate in 3 different modes i.e., Idle, Airplane, and Power Down. In Idle mode, the GPRS radio and other components of GPRS module will remain in "on" state all the time. In this mode, a TCP connection is established for every incoming packet and closed soon after. In Airplane mode, the radio alone can be turned on and off based on user commands. The module however, can continue to buffer packets and accept all commands. We have used this mode effectively to turn on the radio after buffering

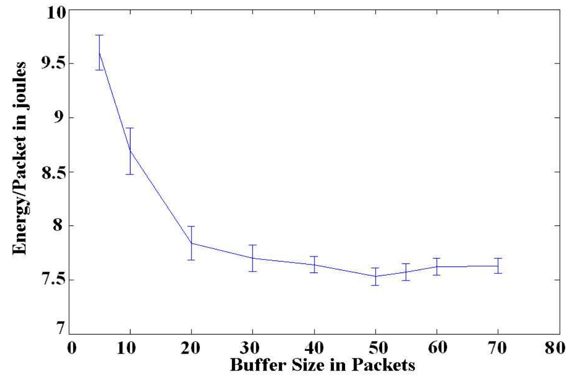
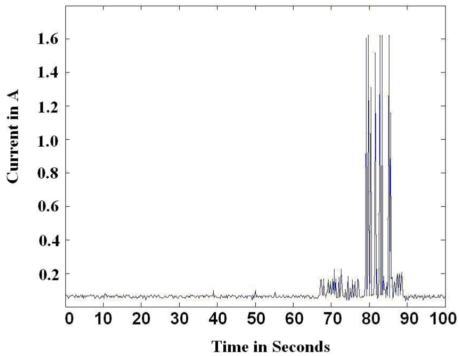


Figure 2: Plot of Energy per packet vs Buffer size for 95% confidence interval

a certain number of packets. Soon after transmission of the buffered packets, the radio is pulled to "off" state. Finally, in power down mode, the entire GPRS module including the radio is turned down. A single command is required to turn on the system.

To calculate the energy overhead due to connection establishment and tear down, we initially conducted an experiment to turn "on" and "off" the GPRS radio. We call this energy overhead as E_C and was evaluated to be about 16 joules. Further experiments were conducted by varying the buffer size and programming the GPRS module in Airplane mode. Once the buffer is full, the GPRS radio is switched to "on" state and a TCP connection is established between the GPRS TCP client and the TCP server located in CEDT. The transmission energy across all buffer sizes is evaluated using the E_T variable. Fig. 2 shows 95% confidence interval of Energy/Packet to transmit. As we increase the buffer size on the module, the transfer energy for a packet decreases until the buffer size is 50 packets. Soon, the energy increases, although very slowly. By taking the 50 packet buffer, our results show that in order to complete a GPRS transfer for a single packet, the minimum amount of energy consumed is 7.5 joules. Thus, for 50 packets, one would require 375 joules. Our metric, the TEB is essentially a per packet energy budget required. For a 5 packet buffer, while the TEB is 9.6 joules, it is 7.5 joules for a 50 packet buffer for successfully transferring data. Finally, we also evaluated the initial energy required as 45 joules by the hardware to boot up. This is the 60 mA constant current drawn and shown in Fig. 3. Assuming that the cyclist runs the dynamo for 20 minutes, the energy generated is sufficient for both to boot up and complete 50 packet buffered data transfer. This demonstrates energy neutrality with a good match in supply and demand in energy.

Table 2 shows the energy required for transferring data over several buffer sizes from the GPRS module. The table also shows the connection overhead ratio. Connection overhead ratio is calculated using the Eq.(2), where E_T is energy required for transmission and E_C is the energy required for connection setup and teardown. Table 2 shows that the TEB reduces as the buffer size increases and marginally increases beyond the 50 packet buffer. The connection overhead en-



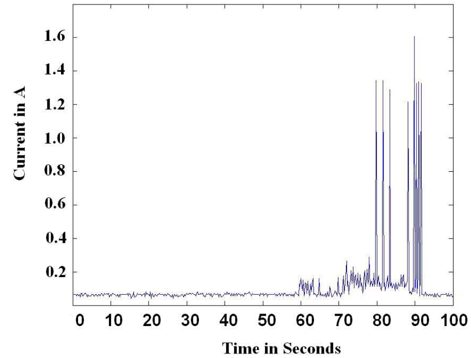


Figure 3: Variation in Current versus time for buffer size 5 and 50 respectively.

Table 2: Energy/Packet and connection Overhead ratio for varying buffer sizes

Buffer Size [Packets]	Time taken to transmit [Seconds]	TEB (per packet) [Joules]	Connection (setup & teardown) Overhead
5	22.2	9.65	0.084
10	23.8	8.85	0.038
20	25.5	7.90	0.022
30	32.4	7.82	0.016
40	37.6	7.64	0.013
50	31.0	7.50	0.011
55	40.9	7.55	0.012
60	43.0	7.62	0.012
70	44.5	7.61	0.012

ergy rapidly reduces as the buffer size increases and at a buffer size of 55 packets, the overhead reaches a minimum saturation value of 0.012.

$$Connection\ Overhead\ ratio = \frac{E_T}{E_T + E_C} \quad (2)$$

Fig. 3 shows the current time series snapshot when the radio turns on with GPRS buffer size of 5 and 50 respectively. The two figures closely compare with the results tabulated and shown in Table 2. For a buffer size of 5 packets, while the time for transfer is shorter, the spiky nature of the current together with the large weight of the overhead energy pushes the energy/packet to a significantly large number. We observe for the 50 packet buffer, the overhead is completely amortized over the transfer time. Thus, the energy/packet is the least. For the 60, 70 packet buffer, the transfer time together with the current drawn by the system is significantly longer and thus increases the energy per packet.

4.2 DTN Bundle Transfer Based on Harvested Energy

The sink node gathers all the packets from the field deployed sensors over a serial link and passes them to the controller board towards data bundling operation. The system unit together forms the field station node. The controller board is based on Intel's Atom processor and boots Ubuntu operating system from a USB pen drive. The controller board also has a Wi-Fi dongle over USB and primarily used as the DTN interface. From the previous section, since we know that a 50 packet buffer meets the required transfer energy budget, we bundle the incoming sensor data into 50 packets bundles. The data mule comprises of a controller (also based on Intel's Atom Processor) and interfaces the Wi-Fi dongle. The hardware associated with the GPRS module is also interfaced to the controller board. This hardware board with GPRS alone runs on harvested energy from the dynamo.

Algorithm 1 DTN Algorithm for Energy based bundle transfer

1: The field station node and the Data Mule establish a connection over Wi-Fi.
2: The dynamo powered data mule estimates its energy $[E_D]$ and sends it to the field station node.
3: The field station node also estimates its energy $[E_F]$.
4: A decision is made to determine the number of bundles "n" to be sent from the field station node based on the minimum energy i.e., $n = \min(E_D, E_F)$.
5: If the energy available is less than the minimum energy required i.e., 420 J, then no bundles are sent by the field station node.
6: The field station node sends the bundles to the data mule and awaits an acknowledgement (ACK).
7: The data mule after receiving a bundle, transfers the bundle into the GPRS buffer for transmission to the remote server over GPRS. On successful delivery at the remote server, the data mule sends an ACK back to the field station node.
8: The field station node deletes all successfully acknowledged bundles.
9: If the data mule has more energy, at least 420 J, the data mule puts up a fresh request and Steps from 2 to 9 are repeated.

The ladder diagram in Fig. 4 shows the implementation of energy negotiation and data bundle transfer between the field station node and the data mule. Soon after the connection is established, the data mule uses the "DTNCP" command and sends its TEB. The field station unit, on its part also estimates the TEB and transfers the required number of bundles matching the minimum of the TEB. The data mule upon receiving the data bundles, forwards the data into the buffer of GPRS module. We estimated the time for

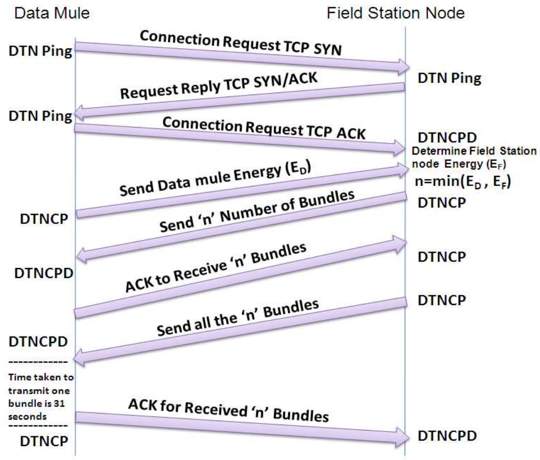


Figure 4: Ladder diagram for transfer of bundles based on the harvested energy.

a 50 packet bundle as 31 s on the data mule from the time the bundle arrives from the field station until the data is transferred successfully over the GPRS. Algorithm 1 completely captures the working of DTN stack.

5. DATA RELIABILITY DISCUSSIONS

Due to hopping nature of the data, the system requires a sufficient level of data reliability. Two separate TCP connections are used for data transfer from the field station to the destination server. The first TCP connection is between the DTN stack up to the GPRS system and ensures that the bundles are transferred into the GPRS module's buffer. The second TCP connection is between the GPRS node and the end server. Further, link layer Automatic Repeat Request (ARQ) increases the reliability. Finally, we have introduced energy based data transfer and ensured that data under any circumstance is not purged until it reaches the end server. Thus, DTN from an energy perspective combined with reliability is a novelty in our proposed scheme. Our scheme also ensures that there are no replaceable components such as batteries. An ideal supercapacitor has infinite charge-discharge cycles and does not require complex charging circuitry.

6. CONCLUSIONS - TOWARDS A SUSTAINABLE MODEL

The model we have proposed becomes sustainable and general enough for application in several scenarios. It is sustainable in the field due to the following two reasons: (a) The farmer has to generate energy (quite like the days of the water wheel!) to take advantages of modern technologies. The success of his crop yield is directly dependant on his own efforts. We think that apart from tilling the land and watering the crop, he has to additionally generate energy for crop information and thus evolve a financially sustainable model. (b) A second reason for sustainability comes from the system we have built. There are no replaceable components such as batteries and associated charging electronics. There is no dependency on grid power and thus operating costs are kept to the bare minimum. The solution is general enough for application in future home networks as well, where home networks require zero downtime. The only way to ensure this in today's world is to make users generate their own power.

7. REFERENCES

[1] Vijay Kalavakonda and Olivier Mahulb, *Crop Insurance in Karnataka*

[2] J. Panchard, S. Rao, T.V. Prabhakar,H.S. Jamadagni,J.P. Hubaux. COMMON-Sense Net: Improved Water Management for Resource-Poor Farmers via Sensor Networks. *In: International Conference on Information and Communication Technologies and Development, 2006.*, ICTD 2006, May 2006.

[3] T.V. Prabhakar,H.S. Jamadagni,Amar Sahu, R. Venkatesha Prasad. Lessons from the Sparse Sensor Network Deployment in Rural India. *In: 11th International Conference ICDCN, 2010.*, ICDCN 2010, Jan 2010.

[4] G. Anastasi, M. Conti, M. Di Francesco. Data collection in sensor networks with data mules : An integrated simulation analysis. *In: Computer and Communications IEEE Symposium, 2008.*, ISCC 2008.

[5] Chang-Jie Jiang, Chien Chen, Je-wei chang, Rong-Hong Jan, Tsun Chieh chiang Construct Small World's in Wireless networks using data mules. *In: IEEE conference on Sensor networks ubiquitous and thrustworty computing, 2008.*, SUTC 2008.

[6] G. Anastasi, M. Conti, Emmanuele Monaldi, Andrea Passarella An Adaptive Data-transfer protocol for sensor networks with data mules. *In: IEEE conference on World f wireless,Mobile and Multimedia Application, 2007.*, Wowmom 2007.

[7] Ryo Sugihara, Rajesh K Gupta Optimizing Energy-Latency Trade-Off in Sensor Networks with Controlled Mobility. *In: IEEE conference on INFOCOM,2009.*, INFOCOM 2009.

[8] Kevin Fall, Stephen Farrell DTN : An Architectural Retrospective. *In: IEEE Journal on selected areas in Communications,2008.*, VOL 26, No 5, June 2008.

[9] S Dimitriou ,V Tsaoussidis. Effective Buffer and Storage Management in DTN nodes. *In: Ultra modern Telecommunications and workshops,2009.*, ICUMT 2009.

[10] Young Li, Meng Jiong Qian, Depeng Jin, Li Su, Lie Guang Zeng. Adaptive Optimal buffer Management policies for Realistic DTN. *In: IEEE proceedings GlobeCom ,2009.*, GLOBECOM 2009.

[11] F Gil-Castineira, F.J Gonzalez-Castano, R. Asorey -Cacheda, L. Framck and S. Paillard Practical development of an Embedded Hybrid Wireless DTN node. *In: Satellite and Space Communications, 2006 International Workshop.*, Sept 2006.

[12] Shockfish

[13] XE1205 TrueRF

[14] Delay Tolerant Networking Research Group