Power Consumption Analysis for Mobile Stations in Hybrid Relay-assisted Wireless Networks

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***Abstract*—While Internet access using mobile or wireless technologies has become ubiquitous these days, the energy consumption aspect of such connections has not been studied in-depth yet. In this paper, a hybrid wireless network, which consists of a cellular component and a relay-assisted ad hoc component, is studied focusing on energy consumption by mobile stations with respect to the amount of data communicated and achieved battery lifetime. Four alternative paths are considered, including both pure cellular and hybrid ad hoc/cellular links for uplink and downlink traffic. The effects of each alternative connection on energy consumption of the involved mobile stations are analyzed in terms of the amount of data transferred and the operation time of the station's battery. The results from our analysis can also be used for proper relay selection in a hybrid link for achieving optimum data transfer from the Internet while keeping battery energy consumption of the mobile station and/or the relay station at a minimum level.**

I. Introduction

Internet access has spread rapidly over the globe in recent years, thanks largely to the availability of both cellular and wireless technologies. To access the Internet through wireless connections, one may use either infrastructure-based cellular networks or infrastructure-less ad hoc networks [1]. In a cellular network, users are connected to the Internet via a Base Station (BS). Using an ad hoc link, a user may also access the Internet via either a direct link or through intermediate cooperating nodes, called Relay Stations (RSs). Generally speaking, the supported one-hop data rate for ad hoc networks, which operate typically based on the IEEE 802.11 standard [4], is higher than its cellular counterpart, while the communication range for these two types of networks behaves oppositely.

Due to their mobile nature, most wireless devices, e.g., hand-held Mobile Stations (MSs), are battery powered. This places a strict limit on the amount of energy they can store in their batteries. Consequently, this requires efficient utilization of the battery power. In such a context, it is of importance to understand the relationship between MS/RS power consumption and other factors like data communicated and network connectivity, and to further develop strategies for efficient power utilization.

Although architectures for wireless Internet access have been proposed and various solutions exist, little attention has been paid to the energy consumption aspect of these solutions. For example, the Unified Cellular and Ad hoc Network architecture (UCAN) [3] considers MSs with dual mode interfaces, i.e., an IEEE 802.11 ad hoc mode and a cellular mode. This architecture prefers multi-hop packet forwarding for throughput improvement when the signal quality in the downlink channel between the BS and the MS is poor. However, the energy consumption on the IEEE 802.11 interface is analyzed merely to compare certain protocols in terms of routing overhead. Another architecture, the upcoming IEEE 802.21 standard [2], proposes a framework for devices to choose access alternatives among multiple available networks. However, it does not specify any energy parameters/constraints affecting the energy consumption of a wireless station for selecting a best-connected network. How energy consumption of a station's battery may affect the amount of communicated data is not considered in this architecture either.

In this paper, an energy consumption analysis is performed for the MS/RS which is part of a Hybrid Network (HN) composed of both a cellular component and an ad hoc component. The MS may access the Internet through the BS either directly or via an intermediate RS. Four alternative paths for uplink and downlink traffic are considered for the MS. The energy consumption by the MS and the RS is computed for these possible paths by taking into account the effects of the distance from the MS/RS to the BS and the path-loss coefficient on energy consumption. Furthermore, how the selection of different path for uplink and downlink traffic may affect power consumption is also investigated. The obtained results may be used for selecting a path which leads to maximal amount of upload/download traffic while keeping optimal battery consumption.

The rest of the paper is organized as follows. In Sec. II, the scenario of the studied HN is described along with a few basic assumptions. Sec. III performs energy consumption analysis for the MS (and/or RS) over different available links. The numerical results are presented and discussed in Sec. IV and Sec.V respectively for symmetric and asymmetric traffic, before the conclusions are drawn in Sec. VI.

II. Hybrid Network Scenario and Assumptions

In this section, we describe the hybrid network architecture under consideration for this study. As illustrated in Fig. 1, the overall HN is divided into two alternative network components, i.e., an ad hoc component and a cellular component. The direct cellular link between the MS (or the RS) and the BS supports lower data rate and hence referred to as a Low Data Rate (LDR) link. The ad hoc link between the MS and

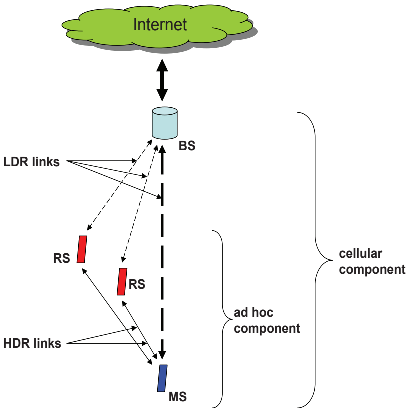


Fig. 1. Basic hybrid network architecture.

an RS (which is simply another MS) is referred to as a High Data Rate (HDR) link. The BS is assumed to be without power constraint while the MS and RS(s) are battery powered. While the distance between the MS/RS and the BS plays a role in our calculation later, we assume simply that the MS and the RS are within the coverage of each other.

The MS may establish communication with the Internet via the BS through four possible connections, i.e., (1) a direct cellular connection for both uplink and downlink, referred to as *direct cellular connection*; (2) a *hybrid connection*, in which all uplink and downlink traffic between the MS and the BS has to go through an RS; (3) a mixed Uplink Cellular and Downlink Hybrid *(UCDH) connection*, in which the cellular link is used for uplink traffic while the hybrid link is used for downlink traffic; and (4) a mixed Uplink Hybrid and Downlink Cellular *(UHDC) connection*, in which traffic goes in an opposite direction than that in UCDH.

Furthermore, Code Division Multiple Access (CDMA) is assumed for the cellular/LDR link while Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) [4] is assumed for the ad hoc link. For power consumption calculation later on, we focus on power consumed by the transmission, reception and processing processes for a frame. Other activities such as tranmission/reception state transition, idle-mode etc are assumed to consume negligible energy.

Moreover, for calculation convenience, only one transmission cycle is used in the ad hoc link. The RS has sufficient buffer size to store the incoming data before forwarding it to the next station. The control and *DATA* frames are not lost and are received as error-free packets and the propagation delay for packet transmission is neglected. For our calculation in the cellular mode, a simple path-loss model [5] is utilized along with a condition imposed on the difference of signal levels observed on the receiving station in CDMA systems [6].

III. Power Consumption Analysis

The analytical work described in this section is focused on the calculation of the power (and hence, the energy or the energy per bit)[1] consumption by the MS and the RS for the four alternative connections described above.

In what follows, we perform the calculation of power consumption per bit of a station first in the ad hoc mode and then in the cellular mode, for both packet transmission and packet reception during one complete transmission cycle. This also enables us to further calculate the partial energy consumption of a station in the hybrid, UCDH, and UHDC connections.

A. Energy Consumption in the HDR Ad Hoc Link

According to CSMA/CA, the atomic interactions between the MS and the RS are illustrated in Fig. 2. In this figure, the solid amplitude level of a frame implies that the main power contribution in this frame is due to transmission. Similarly, the dotted amplitude levels indicate power consumption for reception.

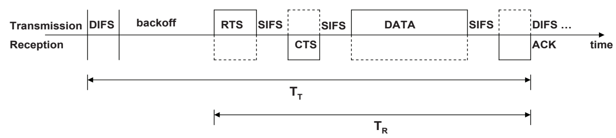


Fig. 2. Atomic interaction between transmitter and receiver for HDR link.

By using Fig. 2, the *total power* consumed in the ad hoc mode by a station for the transmission of a $DATA$ frame and transmission/reception of its associated control frames for a single transmission cycle can be given as

$$P_{tr\_adhoc} = \{T_{DIFS}P^{e}_{DIFS} + E[T_{bo}]P_{bo} + T_{RTS}P^{t+e}_{RTS} + 3T_{SIFS}P^{e}_{SIFS} + T_{CTS}P^{r+e}_{CTS} + T_{DATA}P^{t+e}_{DATA} + T_{ACK}P^{r+e}_{ACK}\}/T_T \quad (1)$$

where e, t, and r in the supersctiprs of the variable P are, respectively, for the power consumed in electronic processing, transmission, and reception phases of the corresponding frames. The subscript bo implies $backoff$. The variable T, with a subscript, self-sufficiently represents the time consumed by a corresponding frame. T_T, representing the total time taken by the $DATA$ and associated control frames, is given by

$$T_T = T_{DIFS} + E[T_{bo}] + T_{RTS} + 3T_{SIFS} + T_{CTS} + T_{DATA} + T_{ACK}. \quad (2)$$

In a similar way, we can express the total power consumed in the ad hoc mode by a station for the reception of a $DATA$ frame and the transmission/reception of the associated control frames. That is

$$P_{re\_adhoc} = \{T_{RTS}P^{r+e}_{RTS} + 3T_{SIFS}P^{e}_{SIFS} + T_{CTS}P^{t+e}_{CTS} + T_{DATA}P^{r+e}_{DATA} + T_{ACK}P^{t+e}_{ACK}\}/T_R \quad (3)$$

[1]Given power consumption, energy consumption and energy consumption per bit can simply be calculated by using $Energy = Power \times Time$ and $Energy = Power/Datarate$ respectively.

where T_R represents the total amount of time taken by the $DATA$ and associated control frames, and is expressed as

$$T_R = T_{RTS} + 3T_{SIFS} + T_{CTS} + T_{DATA} + T_{ACK}. \quad (4)$$

The relationship between energy and power can now be applied to Eqs. (1) and (3) in order to obtain the corresponding energy consumption by an ad hoc station for transmission and reception of the $DATA$ and associated control frames.

B. Energy Consumption in the LDR Cellular Link

Consider in Fig. 1 that two mobile stations, i.e., an MS and an RS, are transmitting towards the BS at the same time. To meet the fundamental requirement in CDMA that the difference between the received signals at the BS must remain within 1 dB [6], we can write

$$\left| \frac{G_1 P_{t_1}}{d_1^{\alpha}} - \frac{G_2 P_{t_2}}{d_2^{\alpha}} \right| \leq 1dB \quad (5)$$

where P_{t_1} and P_{t_2} are the transmission power of these two stations respectively, d_1 and d_2 are the distances from the MS and the RS to the BS respectively, G_1 and G_2 are unitless constants that depend on corresponding antenna characteristics, and α is path-loss constant. The relationship between transmission power and distance is taken from the simplified path-loss model as $P_{rec} = GP_{tr}/d^{\alpha}$, where P_{rec} represents the received power.

The power consumed per bit by the MS, P_{cb}, has two major components[2], i.e., the power needed in order to generate P_t amount of transmission power, and the electronic processing power of the transceiver circuitry used mainly to encode/decode the transmitted/received signal. Therefore, we have [8]

$$P_{cb} = m_1(P_{et} + P_t) + m_2(P_{er}) \quad (6)$$

where P_t is the transmission power, and P_{et} and P_{er} are the electronic processing power for transmission and reception, respectively. The binary integers, m_1 and m_2, reflect the status of the communicating radio. Given that the MS radio cannot transmit and receive simultaneously, we have $m_1 = 1$ and $m_2 = 0$ when the MS is in the transmission state and $m_1 = 0$ and $m_2 = 1$ when it is in the reception state.

Since, in general, more circuitry is required to receive and decode the signal, we can relate P_{et} and P_{er} as $P_{er} = 2.5P_{et}$ [9][3]. Hence, Eq. (6) becomes

$$P_{cb} = m_1(P_{et} + P_t) + m_2(2.5P_{et}). \quad (7)$$

All the above formulas in this subsection also apply to the RS for the corresponding power consumption calculations.

The average energy consumption, E_{cb}, of the MS/RS per communicated byte in the cellular link can now be calculated as

$$E_{cb} = 8 \times P_{cb}/R \quad (8)$$

[2]It is worth mentioning that P_{cb} is the power *consumed by the MS* (not the transmission power) in order to generate P_t amount of transmission power; and $P_{cb} \neq P_t$.

[3]As suggested in [9], P_{er} is usually 2 to 3 times higher than P_{et}.

where R is the supported cellular data rate.

To investigate the effects of the position of the MS on the battery energy consumption, the transmission power of the signal needs to be taken into consideration. Hence, the MS is required to adjust its P_t in order to satisfy Eq. (5). This also influences the corresponding energy consumption of the battery. The variation of the energy consumption per byte for the MS with respect to the varying distance from the BS, when another MS/RS is also transmitting at a power level of 300 mW from a constant distance of 600 meters from the BS, is shown in Fig. 3.

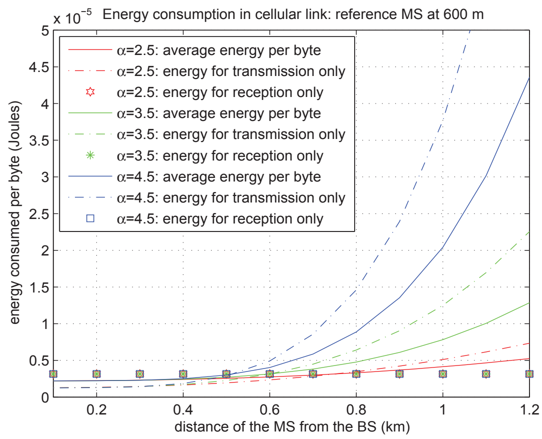


Fig. 3. Effects of distance and α on the energy consumption in cellular link.

From this figure, it is evident that higher values of α (i.e., worse channel conditions) and longer distance from the BS increase the corresponding energy consumption by the MS because higher P_t is required to reach the BS. Similar reasoning also applies to the RS when it operates in the cellular mode. For example, in Fig. 1, the requirement on P_t for the RS which is closer to the BS is lower than the one which is placed farther from the BS. Hence, an RS which is lying closer to the BS consumes relatively lower amount of energy per byte, provided that all the other relevant parameters are kept the same. Similar trend can also be observed with the increasing values of α.

Another interesting observation from Fig. 3 is that the energy consumption for reception-only is higher than both the energy consumption for transmission-only and the average energy consumption when the MS is closer to the BS. The reason for this effect is the smaller contribution of d and α to the average energy consumption when the MS is closer to the BS and channel conditions are moderate. This result gives us a hint on using the MS in cellular mode for only uploading the data when it is closer to the BS.

C. Energy Consumption in Mixed Connections

As discussed earlier, there are two types of mixed connections considered in this work: UCDH and UHDC. For the UCDH connection, the MS transmits via the cellular link and receives via the ad hoc link. The corresponding total power consumption per byte, $P_{tot\_UCDH\_MS}$, of the MS becomes

$$P_{tot\_UCDH\_MS} = [P_{et}+P_t]_{per\_byte}+[P_{re\_adhoc}]_{per\_byte}. \quad (9)$$

Correspondingly, the total power consumption per byte, $P_{tot\_UCDH\_RS}$, for the RS in the UCDH connection can be expressed as

$$P_{tot\_UCDH\_RS} = [P_{er}]_{per\_byte} + [P_{tr\_adhoc}]_{per\_byte}. \quad (10)$$

Similarly for the UHDC connection, the total power consumption per byte, $P_{tot\_UHDC\_MS}$ and $P_{tot\_UHDC\_RS}$, for the MS and the RS becomes respectively

$$P_{tot\_UHDC\_MS} = [P_{tr\_adhoc}]_{per\_byte} + [P_{er}]_{per\_byte}. \quad (11)$$

$$P_{tot\_UHDC\_RS} = [P_{re\_adhoc}]_{per\_byte} + [P_{et} + P_t]_{per\_byte}. \quad (12)$$

The subscripts in the above four equations are self-explanatory. The corresponding energy consumption values can now be obtained by using the conventional relation between power and energy.

IV. Numerical Results and Comparison

To evaluate the performance of the system with different parameters, MATLAB is utilized as the tool. For the ad hoc link, an access protocol similar to CSMA/CA is used to calculate the energy consumption of a station. The data rates of 11 Mbsp and 348 Kbps are used, respectively, for the HDR ad hoc link and the LDR cellular link. The values of α are taken as 2.5 and 4.5 respectively. The representative distances of a station in the cellular mode are taken as 400 meters and 900 meters from the BS. Extra protocol overhead is neglected for the numerical calculation of energy consumption. The initial value of the battery energy is taken as 50 Joules. The other parameters used in the evaluation of the ad hoc link are summarized in Table I [10].

TABLE I
AD HOC LINK ANALYSIS PARAMETERS.

Parameter	Value	Parameter	Value
basic rate	1 Mbps	$DATAframe$	300 bytes
data rate	11 Mbps	T_{SIFS}	10 μs
$E[T_{bo}]$	80 μs	T_{DIFS}	50 μs
T_{RTS}	$20 * 8$/basic rate	P^t	800 mW
T_{CTS}	$14 * 8$/basic rate	P^r	484 mW
T_{ACK}	$14 * 8$/data rate	P^e	100 mW
		P_{bo}	3.2 mW

Fig. 4(a,b) through Fig. 7(a,b) illustrate, respectively, the amount of transferred data and the battery operation time for the MS (and/or the RS) in different connections with respect to the remaining battery energy. A negligible amount of energy consumption is assumed for connection maintenance with the BS when the MS is downloading or uploading the data from/to the Internet. Four different options for data exchange with the BS (and the Internet, thereof) are discussed in the following two sections. While more attention has been given to symmetric Internet traffic with the results illustrated in Figs. 4, 5, and 6, the corresponding results for asymmetric traffic are dealt with in Section V.

A. MS with Direct Cellular Connection

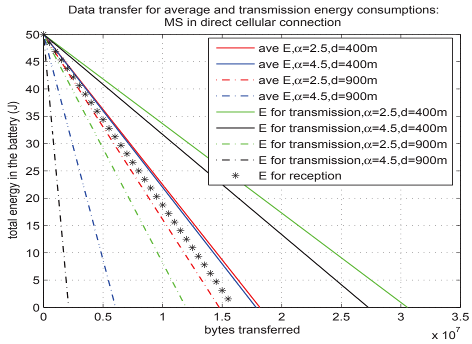
Fig. 4 shows the amount of data exchanged and the battery operation time for the MS respectively, with only the direct cellular link. In this figure, *ave E* implies the average energy consumed for both transmission and reception of bytes. As evident from the figure, relatively more bytes are transferred when the MS is closer to the BS and α is smaller. The reason for this result is that a lower amount of P_t is required to reach the BS when the MS is closer to the BS, under moderate channel conditions. However, given small values of α and d, i.e., 2.5 and 400 m, for the same amount of consumed energy, more bytes are transferred when the MS is transmitting-only (see solid green plot) than when it is both transmitting and receiving (see solid red plot). Moreover, when the MS is farther away from the BS (i.e., $d = 900$ m) and $\alpha = 2.5$, transmission-only (i.e., uploading) requires more energy and hence a lower amount of data is transferred than the average energy consumption case (compare the dotted red and green curves).

Furthermore, for the same amount of consumed energy, a higher number of total bytes is received when the MS is utilized only for reception (downloading) at a longer distance from the BS ($d = 900$ m) than when it is utilized both for uploading and downloading from the BS (see the black-star plot in Fig. 4). The reason for this result is that when the MS both uploads and downloads data, it consumes energy for both transmission and reception, and hence, the average energy (averaged inclusive of both the energy consumption for transmission and reception) is higher than the energy consumption for transmission-only. However, for shorter distance ($d = 400$ m), the energy consumption is lower, and the MS, when used only for transmission, transfers more data for the similar amount of consumed battery energy. Therefore, for a larger d, the MS operated only for reception gains more in terms of downloaded amount of data. However, with a smaller d, the MS obtains better benefit when used for uploading-only than when used for both uploading and downloading. Consequently, *when using direct cellular connection, we should use the MS for downloading-only if it is placed farther away from the BS ($d = 900$ m); and use for uploading-only when it is placed closer to the BS.* Combined uploading and downloading consumes energy roughly comparable to the energy for downloading-only, when the MS is placed closer to the BS ($d = 400$ m).

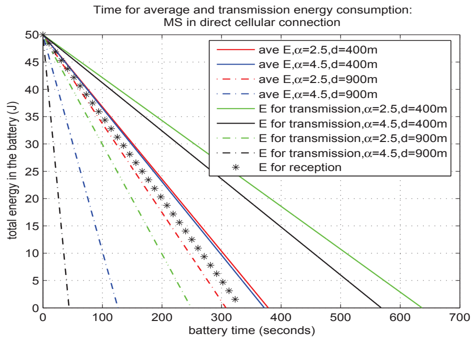
Similar trends, as discussed in the above two paragraphs, are observed in Fig. 4(b) for battery operation time. The reasons for the plots are also similar to those described for Fig. 4(a).

B. MS with Hybrid Connection

Fig. 5 shows the amount of transferred data and the battery operation time for average energy consumption of the RS in the hybrid connection. For simplicity, yet generality, we describe only the case for RS. For the hybrid connection, the RS receives from the MS in the ad hoc mode and transmits to the BS in the cellular mode, when the MS intends to upload. The RS receives in the cellular mode from the BS

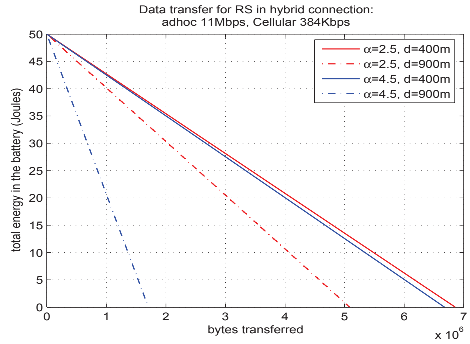


(a)

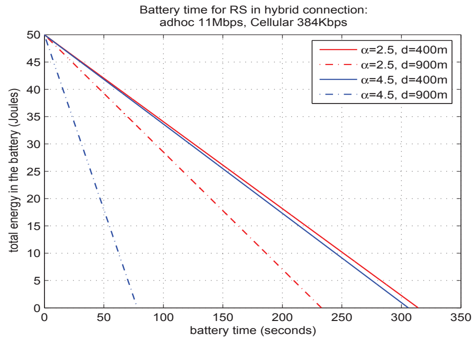


(b)

Fig. 4. Direct cellular connection: relation between remaining energy of MS and (a) bytes communicated (b) battery time.



(a)



(b)

Fig. 5. Hybrid connection: relation between remaining energy of RS and (a) bytes communicated (b) battery time.

and transmits to the MS in the ad hoc mode when the MS intends to download. Average energy consumed per byte by the RS is taken as the average of the energy consumed both for transmission and reception in the respective modes.

As shown in Fig. 5(a), for the same amount of consumed energy in the hybrid connection, the total quantity of the transferred data for the specified values of α and d is, in general, lower than that for the MS in the direct cellular connection (in comparison with Fig. 4(a)). This result is because of the higher contribution of energy consumption from the ad hoc link toward the average energy consumption as well as the two-way cooperation of the RS. The effects of α and d for the RS are consistent to those for the MS in Fig. 4(a). *Hence, an RS placed closer to the BS gains more than the one placed farther, both in terms of amount of transferred bytes as well as battery operation time, for the same amount of consumed energy.*

In Fig. 5(b), the total battery time for the RS is lower than the corresponding values for the MS in the direct cellular connections. The reason for this effect is that a relatively higher amount of energy is consumed by the HDR ad hoc part of the hybrid connection, leading to shorter total operation time. As expected, the effects of α and d are consistent as what is observed earlier.

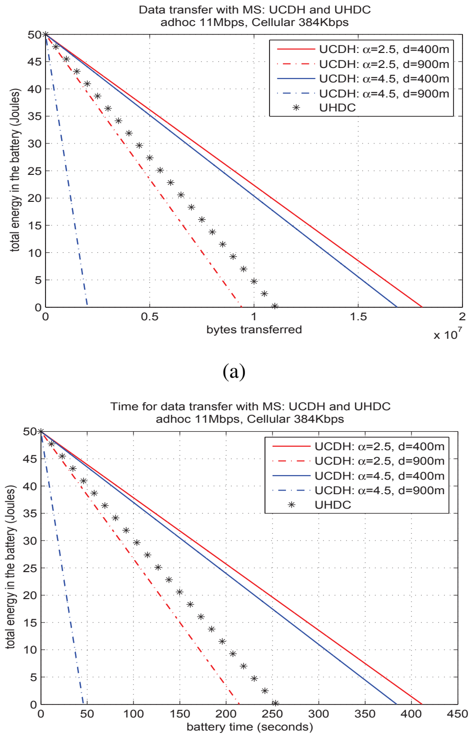
C. MS with Mixed Connections: UCDH and UHDC

In Fig. 6 the amount of transferred data and the battery operation time are shown, respectively, when the MS is operating in the mixed connections. The black-star plot in Fig. 6(a,b) represents the UCDH connection and the remaining plots represent the UHDC connection. When the UCDH connection is used by the MS, for the similar amount of consumed energy, it gains more in terms of both time and bytes as compared with the UHDC connection, when the MS is located closer to the BS and α is smaller. The reason for this result is the lower transmission power requirement, for the cellular uplink part of the UCDH connection, with shorter distances and lower α. However, for larger d and α, the UHDC connection has advantage over the UCDH connection. *Hence, when using mixed connections, if the MS is located closer to the BS, uploading through UCDH connection and downloading through UHDC connection achieves better performance.*

By comparing Fig. 6(b) with Fig. 5(b), we also observe a clear advantage for the battery time of the MS at shorter-distance with the mixed connection over the battery time of the RS when used in the hybrid connection. However, the direct cellular connection, in general, gains more battery lifetime except for the cases with longer distance and poor channel conditions in terms of the average energy consumption by the MS.

V. Performance with Asymmetric Traffic

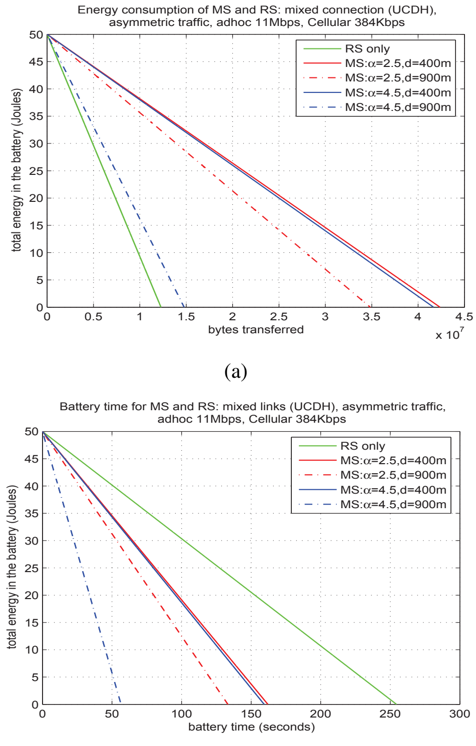
In general, the Internet traffic is not symmetric. Hosts usually use relatively smaller amount of bytes for uploading than for downloading. Hence, we discuss some of the results achieved through our analysis with reference to asymmetric



(a)

(b)

Fig. 6. Mixed links: relation between remaining energy of MS and (a) bytes communicated (b) battery time.



(a)

(b)

Fig. 7. Mixed UCDH connection, asymmetric traffic: relation of remaining energy of MS and RS on (a) bytes communicated (b) battery time.

Internet traffic. For this part of our study, it is assumed that 90% of the traffic is for downloading and 10% is for uploading the data.

We have evaluated the effects of asymmetric traffic on the energy consumption of both the MS and the RS for the mixed UCDH as well as UHDC connections. However, due to page limit, only the mixed UCDH is discussed below.

For the UCDH connection, the amount of transferred bytes both for the MS and the RS are illustrated in Fig. 7(a), for the same amount of battery energy consumption. Comparing this figure with Fig. 6(a), we observe that the MS obtains more benefits in terms of transferred bytes, because it is using a major part of the energy for downloading only. Hence, for realistic asymmetric traffic, the MS used in the UCDH connection performs better than for the symmetric traffic. However, in terms of the battery time, the asymmetric traffic is outperformed by the symmetric traffic, as evident from the comparison of Fig. 7(b) with Fig. 6(b). Finally, although not explicitly shown in the figure with respect to α and d, the RS lasts longer in asymmetric UCDH connection, in general.

VI. Conclusions and Future Work

In this paper, we have proposed an approach to estimate energy consumption of an MS/RS equipped with dual interfaces in a wireless HN scenario. Using the proposed mobile-oriented analysis for energy consumption, the magnitude of communicated data bytes and the battery operation time can be calculated for different choices of uplink and downlink paths for the MS/RS to and from the Internet. The results suggest that different choices of paths as well as next-hop links exist for both uploading and downloading to/from the Internet in order to optimize the magnitude of communicated data and the total battery lifetime. As our future work, a feasible energy-based policy will be developed for MS/RS to optimize the above mentioned parameters.

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