Multi-mode relay simulations: an energy evaluation on WSNet

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***Abstract*— Relaying provides one of the most interesting solutions to reduce the energy consumption for both the terminals and the network. However, energy evaluation requires a high degree of realism. This paper introduces a realistic energy model to evaluate the energy consumption of multi-mode Software Defined Radios terminals, from a physical layer point of view. It explains the development of multi-mode modules for WSNet, a precise network simulator. It presents WSNet as a pertinent tool to evaluate the energy consumption of an 802.15.4-to-802.11g relay, and shows that multi-mode relaying does not always lead to energy reductions.**

I. INTRODUCTION

Energy reduction is a hot topic in modern mobile networks. Several solutions have already been proposed in literature. This paper takes the approach of relaying, which provides a well known solution to increase the network lifetime or coverage, as show by Cavalcanti et al., where users terminals act as mobile relays [1]. With modern terminals being naturally multi-mode, they can communicate through different interfaces at the same time.

The evaluation of energy consumption requires a realistic approach. In this paper, we propose a realistic energy model to evaluate the energy consumption of multi-mode terminals. We extend this model to include MAC layer and relaying. We use *Software Defined Radios* (SDR) terminals as a convenient way to implement multi-mode. An SDR features a generic processor running programs, which are shared between the implemented communication modes.

Contrary to strictly analytical approaches, network simulations allow an easier integration of realistic parameters. However, previous energy-related works only evaluate the consumption of mono-mode relays. Gao et al. analyse the gains of cooperative relays in wireless sensors under realistic assumptions [2]. Zhang et al. evaluate opportunistic relaying from a physical layer point of view, considering a realistic MAC layer [3]. In this work, we explain our implementation of multi-mode in WSNet, a precise network simulator [4]. We consider multi-mode terminals, capable to communicate either on IEEE 802.11g [5] or 802.15.4 [6] protocols. We evaluate the energy consumption of a multi-mode relay scenario (*i.e.* 802.15.4-to-802.11g), through realistic network simulations.

We explain our realistic energy model for multi-mode terminals in Section II. Then, we present our implementation of multi-mode in WSNet in Section III. We perform realistic simulations to evaluate the energy consumption of a multi-mode relay scenario, in Section III. We show that WSNet can be used as a tool for realistic energy evaluation. Finally, we conclude in Section V.

II. ANALYSIS OF MULTI-MODE ENERGY CONSUMPTION

In this section, we present a realistic energy model. We separate the transmission (TX) and the reception (RX).

A. Energy per bit for a communication mode

The energy of a multi-mode terminal, τ_i, is shared between all its communication modes, $M(\tau_i)$. Each communication mode, $m_j \in M(\tau_i)$, has its own specifications (modulation, coding, etc...). Hence, to evaluate the terminal energy consumption, the first step is to consider each mode independently.

In order to compare different modes, we evaluate the energy per (user data) bit for a mode m_j, denoted $E_{\text{bit}}(m_j)$. On an SDR, a mode is split into two parts: the numerical energy consumption, $E_{\text{num}}(m_j)$, determined by the generic processor which realizes baseband and signal processing, and the radio energy consumption, $E_{\text{rf}}(m_j)$, tied to the radio frequency front-end. Hence:

$$E_{\text{bit}}(m_j) = E_{\text{num}}(m_j) + E_{\text{rf}}(m_j) \tag{1}$$

The numerical energy of a mode m_j, denoted $E_{\text{num}}(m_j)$, is the energy required to process one data bit. It is expressed in Joule per bit as [7]:

$$E_{\text{num}}(m_j) = K\ E_{\text{cpu}} = K\ A_C\ V_{dd}^2 \tag{2}$$

with K the number of operations per bit (or *bitop*) and $E_{\text{cpu}} = A_C\,V_{dd}^2$ the processor consumption for one operation (in Joule). The processor switching capacitance, A_C (in Farad), and its input voltage, V_{dd}^2 (in Volt), are defined by the processor specifications. K depends on the algorithm implementation and the processor specifications.

The radio energy consumption of a mode m_j, $E_{\text{rf}}(m_j)$, is the energy consumed by an active radio front-end to send/receive one data bit [8]:

$$E_{\text{rf}}(m_j) = \frac{1}{R_j}(P_{\text{frontend}} + \theta P_{\text{out}}) \tag{3}$$

with R_j the mode data bit rate (in bits per second), P_{frontend} the radio front-end energy consumption (in Watt),

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based on the constructor specifications, P_{out} the transmission power output (in Watt), and $\theta = 1$ defining transmission (0 otherwise).

B. Enhanced energy model, accounting the MAC layer

In multi-mode, each mode has its own MAC layer: it defines the channel access method and the frame size. In order to evaluate the energy per bit, we recover $\bar{b}$ the number of bits sent for each useful data bit as follows:

$$\bar{b} = \frac{S(f_j) + S(\text{MAC}_j)}{b_0} \tag{4}$$

with $S(f_j)$ the data size of MAC frame f_j in mode m_j, $S(\text{MAC}_j)$ the size of MAC control packets in mode m_j, and b_0 the original data size from the application. All sizes are in bits.

In this part, we study the influence of control packets on E_{bit} when transmitting a MAC frame f_j of size $S(f_j)$. We consider a random access MAC layer, such as *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) used in 802.11g. In CSMA/CA, when a source desires to send data to a destination, it first listens to the channel for a given period, called T_{L}. If the channel if free, the source sends a *Request to Send* (RTS) packet. Otherwise, the source draws a random backoff and sleeps during a corresponding time, called T_{B}. This process is repeated until the channel is free or the backoff retry count is reached. When the destination receives the RTS packet, it replies a *Clear to Send* (RTS) packet. The source transmits data to the destination, which acknowledges good reception with an *Acknowledgement* (ACK) packet. The communication is successful when ACK is received before the timeout period, T_{To}, during which the source listens.

We now detail the energy consumption of terminal τ_i for a frame transmission in mode m_j, considering CSMA/CA. The numerical energy consumption to transmit one bit, $E_{\text{num}}^{\text{TX}}(m_j)$, is modified as follows:

$$E_{\text{num}}^{\text{TX}}(m_j) = \frac{E_{\text{cpu}}}{b_0} \cdot \left[K^{\text{TX}}\big(S_{\text{RTS}} + S(f_j)\big) + K^{\text{RX}}\big(S_{\text{CTS}} + S_{\text{ACK}}\big)\right] \tag{5}$$

with $K^{[\text{TX,RX}]}$ the bitop in transmission or reception, and $S_{\text{RTS}}, S_{\text{CTS}}, S_{\text{ACK}}$ the size of the corresponding control packet (in bits). Moreover, $S(f_j)$ integrates the intermediate headers and the PHY layer preamble.

The radio energy consumption to transmit one bit, $E_{\text{rf}}^{\text{TX}}(m_j)$, is modified as follows:

$$\begin{aligned} E_{\text{rf}}^{\text{TX}}(m_j) = \frac{1}{b_0} \cdot \Big[&\big(P_{\text{frontend}}^{\text{TX}} + P_{\text{out}}\big)\big(T_{\text{RTS}} + T(f_j)\big) \\ &+ P_{\text{frontend}}^{\text{RX}}\big(T_{\text{L}} + \sum_{r=0}^{\eta}(T_{\text{L}} + T_{\text{B}})_r\big) \\ &+ P_{\text{frontend}}^{\text{RX}}\big(T_{\text{CTS}} + T_{\text{To}} + T_{\text{ACK}}\big)\Big] \end{aligned} \tag{6}$$

with $P_{\text{frontend}}^{[\text{TX,RX}]}$ the radio front-end power in transmission or reception (in Watt), $T(f_j) = \frac{S(f_j)}{R_j}$ the time to send a frame f_j at bit rate R_j, T_{B}, T_{L} and T_{To} as defined previously, η the number of times the channel is sensed busy ($\eta \leq$ Max. Backoff Counter), r the backoff realization, and $T_{\text{RTS}}, T_{\text{CTS}}, T_{\text{ACK}}$ the time to send/receive an RTS, CTS or ACK in mode m_j (allowing independent rates for each packet). Moreover, P_{out} can take into account the higher transmission power for control packets.

C. Energy consumption of a multi-mode terminal

The energy consumption of terminal τ_i, $E_{\text{term}}(\tau_i)$ (in Joule), is the sum of E_{bit} from all its active modes. Hence:

$$\begin{cases} E_{\text{term}}^{\text{TX}}(\tau_i) &= \sum_{j=1}^{m} E_{\text{bit}}^{\text{TX}}(m_j) \quad \forall m_j \in \hat{M}^{\text{TX}}, \hat{M}^{\text{TX}} \subseteq M(\tau_i) \\ E_{\text{term}}^{\text{RX}}(\tau_i) &= \sum_{k=1}^{m} E_{\text{bit}}^{\text{RX}}(m_k) \quad \forall m_k \in \hat{M}^{\text{RX}}, \hat{M}^{\text{RX}} \subseteq M(\tau_i) \end{cases} \tag{7}$$

with $\hat{M}^{\text{TX}}$ and $\hat{M}^{\text{RX}}$ the active modes of τ_i, respectively in transmission and reception, and $E_{\text{term}}(\tau_i) = E_{\text{num}}(\tau_i) + E_{\text{rf}}(\tau_i)$, with $E_{\text{num}}(\tau_i)$ and $E_{\text{rf}}(\tau_i)$ the numerical and radio energy consumption of τ_i.

D. Global energy consumption

We define the *global energy consumption*, E_{global} (in Joule), as the sum of E_{term} from all network terminals:

$$E_{\text{global}} = \sum_{i=1}^{n} E_{\text{term}}(\tau_i) \tag{8}$$

with n the number of energy-constrained terminals.

III. Creating a multi-mode simulator: implementation on WSNet

This section focuses on the implementation of multi-mode in the WSNet simulator.

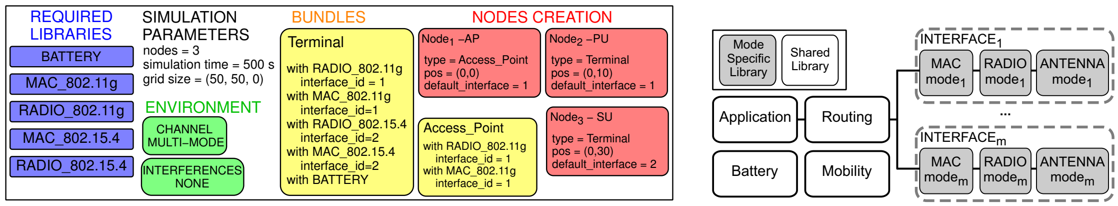
A. WSNet overview

WSNet is a network simulator developed at the CITI Laboratory. It proposes a realistic implementation of several PHY and MAC layers, and a simple energy model. This section presents the necessary steps to create a simulation, with Figure 1 as example.

In WSNet, each terminal (or node) is an assembly of independent *libraries*. The *configuration file* defines their parameters, as presented on Figure 1a. A *bundle* defines the terminal type by linking the libraries together, as depicted on Figure 1b. At *nodes creation*, each terminal (associated to a bundle) is placed on the simulation grid. The granularity of the simulation is tweaked in the configuration file. A multi-mode terminal requires one interface per supported mode. Here, each interface is assigned its own antenna, MAC and PHY layers.

B. Implementation of multi-mode in WSNet

In this section, we present our modifications to handle multi-mode in WSNet. We emphasize the difficulties of such development.



(a) .xml configuration file structure (b) Structure of a terminal (node) in WSNet

Fig. 1: Example of multi-mode WSNet configuration

TABLE I: Example of routing table (excerpt)

Source	Destination	Next Hop	Preferred Interface
a	b	b	1
a	c	b	0
...	...	...	...
c	b	b	2

1) The Application library: sends a given amount of data to a destination. Our modification stores the original data size in the packet. This brings the possibility to evaluate the energy per bit in multi-mode.

2) The Routing library: contains the most important part of our work. Instead of creating an intermediate multi-mode layer, as it is the case in several other works [9], we stick to the OSI model for compatibility purpose. WSNet defines a multi-mode routing table, with an excerpt presented on Table I. The "Preferred Interface" field represents the mode selected to transmit data to the "Next Hop", by a "Source" to reach a "Destination". This mode is stored in the packet header.

3) The MAC layer: takes into account packet fragmentation. It requires knowledge of the maximum frame length per mode. The MAC layer informs the PHY layer to evaluate the energy consumption for a given frame size.

4) The PHY layer: is modified to evaluate the SDR energy consumption per bit, as detailed in section II. It only handles packets of a certain mode, and can also adapts the terminal power output to the receivers' sensitivity.

5) The Antenna and Battery libraries: log uplink and downlink consumptions separately, for each mode.

6) The Mobility library: represents the terminal positions during the simulation and was not modified.

Moreover, we use a multi-mode environment. At the end of the simulation, we recover all E_{term} and E_{global}.

IV. Evaluation of multi-mode relays energy

This section presents an energy evaluation of multi-mode relay scenarios through WSNet simulations.

A. Scenarios presentation: 802.15.4-to-802.11g relay

We evaluate the global energy consumption through simple scenarios featuring three different terminals: an Access Point (AP), a mobile Primary User (PU) and n fixed Secondary Users (SUs). PU and SUs are multi-mode terminals, with a limited energy. AP is mono-mode access point and has no energy constraint.

We implement two scenarios: 1) S_{direct}, where all terminals are in direct communication with AP, and 2) S_{relay}, where n SUs are relayed by one PU on n dedicated connections, and PU is also connected to AP. Here, AP communicates with PU and SUs on 802.11g at 6 Mbps. PU and SUs communicate together on 802.15.4 at 20 kbps.

Simulations are realized on a 30m×30m grid. AP is at the origin. PU moves in straight line toward SUs, from $d_{AP-PU} = 5$m to $d_{AP-SU} = 30$m.

B. Energy evaluation in our scenarios

We evaluate E_{bit} for each mode following Section II. The bitop, K, is computed after [10] for an ARM 968E-S [11]. The radio front-end values are derived from [12] in 802.11g and from [13] in 802.15.4. The values of E_{num} and E_{rf} are summed up on Table II.

We consider independent pathloss models: an indoor ITU-R for 802.11g, with office propagation and three levels of walls [14], and a Friis model for 802.15.4, with a pathloss exponent of 3.1 [15]. Terminals vary their P_{out} following the receiver sensitivity ($RXSens$) and the pathloss. Table III recapitulates the simulation settings.

WSNet allows to measure the influence of several parameters on E_{global}, as presented on Fig. 2. Multi-mode terminals are sensitive to *passive overhearing* (*i.e.* receiving a signal destined to someone else), which is represented by the "jump" at 15m on Fig. 2a. The deactivation of SU's 802.11g interface shows up to 50% gains to E_{global} compared to S_{direct}.

In S_{relay} and S_{direct}, control packets are transmitted at the maximum P_{out}. In "S_{relay} (power-controlled AP)", the limitation of their P_{out} brings around 5% gains in E_{global} compared to S_{relay}, but only before the jump. Afterwards, passive overhearing predominates the energy consumption.

On Fig. 2b, we evaluate the influence of independent Rayleigh channels. In some realisations, S_{relay} may lead to a smaller E_{global}: this is an example of opportunistic relaying. However, in average and considering the standard deviation, σ, we remark the important variations of S_{relay}.

V. Conclusion

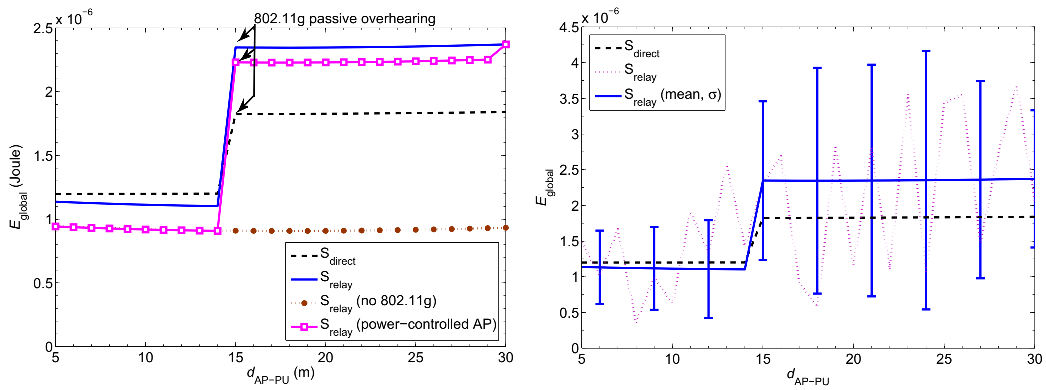
We have presented a realistic energy model to evaluate the global energy consumption of multi-mode relays. We

TABLE II: Terminal energy settings

	K (bitop) [10]	E_{cpu} (nJ) [11]	E_{num} (nJ/bit) (2)	P_{frontend} [12], [13]	E_{rf} (nJ/bit) (3)	P_{out} (dBm)
802.11g @ 6 Mbps	TX: 308 RX: 3,570	0.140	TX: 43.2 RX: 500	TX: 198.8 RX: 338	TX: 56.3 RX: 33.1	-20 to 20
802.15.4 @ 20 kbps	TX: 94 RX: 2,694	0.140	TX: 13.2 RX: 378	TX: 1 RX: 1	TX: 50 RX: 50	-20 to 0

TABLE III: Simulation settings

	R_j	$RXSens$ (dBm)	Pathloss model	MAC Layer	b_0 (bits)	$S(f_j)$ (bits)	$S(\text{MAC}_j)$ (bits)
802.11g	6 Mbps	-87	ITU-R [14]	CSMA/CA	500×8	584×8	S_{RTS} = 288, S_{CTS} = 224, S_{ACK} = 208
802.15.4	20 kbps	-92	Friis [15]	CSMA no RTS/CTS	500×8	540×8	-



(a) Impact of control packets and passive overhearing

(b) With Rayleigh Fading

Fig. 2: WSNet simulations: E_{global} for $n = 1$

have expressed the need of realism, and for this reason, we rely on a network simulator. We have presented our implementation of multi-mode in WSNet and have isolated the parameters influencing the global energy consumption through network simulations.

This paper gives a first insight on the benefits of multi-mode simulations. Future work will evaluate the impact of multi-mode in more complex scenarios (interferences, retransmissions).

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