Toward an energy reduction in mobile relays: combining MIMO and multi-mode

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***Abstract*—The current generation of mobile terminals can communicate on multiple modes using several antennas. However, their energy consumption remains a critical parameter. In this paper, we explore the combination of multiple communication modes and MIMO as a possible way to reduce the energy consumption of both the terminals and the network. We propose a realistic energy model for the PHY layer of a MIMO and multi-mode terminal, taking into account the MAC layer behaviour. We show that the combination of MIMO and multi-mode provides a solution to reduce global energy consumption.**

I. Introduction

Nowadays, mobile users want to stay connected at all times, with modern terminals providing several *communication modes*. Nevertheless, their energy consumption remains a limiting factor. Hence, several techniques have been developped toward energy reduction. For instance, a relay reduces the transmission power and extend the communication range [1]. Moreover, a *multi-mode relay* uses different modes to communicate with the access point and the relayed users, so that the network energy consumption is lowered [2].

With the new generation of protocols, terminals start taking advantage of multiple antennas. *Multiple Input Multiple Output* (MIMO) can provide higher bit rates with a reduced energy consumption at long range, but the gains depend on network density and the channel conditions [3].

In this paper, we explore the combination of MIMO and multi-mode relays on the global energy consumption. For that purpose, we develop a realistic model to evaluate the energy consumption of the PHY layer of a terminal, taking into account the MAC control packets and retransmissions. Then, we consider *Software Defined Radio* (SDR) terminals, as they offer a good way to implement multi-mode and MIMO through agile front-end and multiple antennas.

II. MIMO/multi-mode realistic energy model

In this paper, an SDR terminal, denoted τ, has multi-mode and MIMO capacity. τ implements M modes (Wi-Fi, Zigbee...), and for a given mode $m_j \in M$, it communicates on $N_j^{[\mathrm{TX,RX}]}$ distinct antennas, respectively in transmission/reception.

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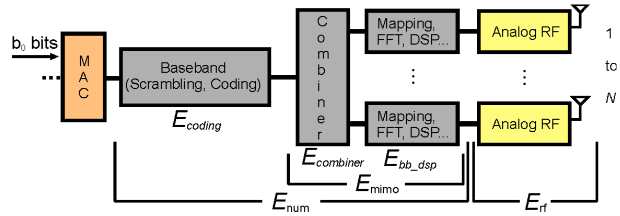


Fig. 1. A communication mode in a MIMO SDR.

A. Energy consumption of a MIMO terminal for one mode

The energy consumption of τ in mode m_j is decomposed as in Fig. 1.

The energy consumption of τ for a communication in mode m_j, $E_{\mathrm{bit}}(m_j)$, is split between its numerical and radio part [2]:

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

$E_{\mathrm{num}}(m_j)$ and $E_{\mathrm{rf}}(m_j)$ are expressed in Joule per bit: they correspond to the energy consumed to transmit (resp. receive) one data bit.

1) Numerical energy consumption: Based on Fig. 1, the numerical energy of τ, $E_{\mathrm{num}}(m_j)$, is expressed as:

$$\begin{aligned} E_{\mathrm{num}}(m_j) &= E_{\mathrm{coding}}(m_j) \\ &\quad + N_j \cdot \left(E_{\mathrm{combiner}}(m_j) + E_{\mathrm{bb\_dsp}}(m_j)\right) \end{aligned} \tag{2}$$

with $N_j \geq 1$ the number of antenna of τ in mode m_j, $E_{\mathrm{coding}}(m_j)$ the energy consumption of the baseband processing on the left of the combiner, $E_{\mathrm{combiner}}(m_j)$ the energy consumption of the MIMO combiner and $E_{\mathrm{bb\_dsp}}(m_j)$ the energy consumption of the baseband and signal processing blocks on the right of the combiner.

2) Radio energy consumption: The radio energy consumption of τ, $E_{\mathrm{rf}}(m_j)$, is expressed as:

$$E_{\mathrm{rf}}(m_j) = N_j \cdot \frac{1}{R_j}\left(P_{\mathrm{frontend}}(m_j) + \theta P_{\mathrm{out}}(m_j)\right) \tag{3}$$

with $P_{\mathrm{frontend}}(m_j)$ the radio front-end power consumption (in Watt), based on the constructor specifications, $P_{\mathrm{out}}(m_j)$ the transmission power output (in Watt), R_j the bitrate of mode m_j (in bit per second), and $\theta = 1$ defining transmission, 0 otherwise.

B. Impact of the MAC layer in the energy consumption

Since E_{bit}, defined in (1), represents the energy consumption for transmitting/receiving one data bit, the MAC layer must be taken into account in the energy evaluation. Hence, the number of bits sent for each useful data bit is denoted $\bar{b}$, and it is defined as follows:

$$\bar{b} = \alpha_f \cdot \left(\frac{S(\text{MAC}) + S(f)}{b_0} \right) \tag{4}$$

with α_f the number of MAC retransmissions before a successful reception of f, $S(f)$ the frame size including headers, and b_0 the data size. Moreover, $S(\text{MAC})$ represents the total size of MAC control packets used for the proper transmission of b_0 data bits. All sizes are in bit.

C. Global energy consumption

In multi-mode, the energy consumption of a terminal τ, denoted $E_{\text{term}}(\tau)$ (in Joule), is the energy consumed by all its modes in communication (in a given scenario).

For a given scenario, the *global energy consumption*, denoted E_{global} (in Joule), is defined as the energy consumption of all terminals involved in the scenario.

III. MIMO multi-mode relay energy evaluation

TABLE I
PARAMETERS TO EVALUATE THE TERMINAL CONSUMPTION

	802.11g	**802.15.4**
Bit rate (R_j)	6 Mbps	20 kbps
E_{cpu}	0.14 nJ$^+$	0.14 nJ$^+$
P_{frontend}		
Transmission	338 mW [4]	1 mW‡ [5]
Reception	198.8 mW [4]	1 mW‡ [5]
P_{out}		
Minimum	−20 dBm	−20 dBm
Maximum	10 dBm	0 dBm
$RXSens$	−87 dBm	−92 dBm
Path-loss (PL)	ITU-R (3 walls)	Friis (factor 3.1)
Carrier Frequency	2.4 GHz	868 MHz

$^+$This value is derived from [6] for one operation.
‡ [5] is a 802.15.4 transceiver using 3.28 mW in transmission and 3.29 mW in reception. As we separate the num. and radio part, we reduce P_{frontend} to 1 mW.

TABLE II
OPERATIONS PER BIT OF THE PHYSICAL LAYER FOR 2 ANTENNAS

Ops/bit, K	**802.11g**		**802.15.4**	
	TX	RX	TX	RX
Coding	103	184	19	19
Combiner	3	4	15	20
Baseband, DSP	2×205	$2 \times 3,386$	2×75	$2 \times 2,675$

TABLE III
NUMERICAL ENERGY CONSUMPTION FOR 2 ANTENNAS (NJ/BIT)

	802.11g		**802.15.4**	
	TX	RX	TX	RX
E_{coding}	14.4	25.8	2.7	2.7
E_{combiner}	0.4	0.6	2.1	2.8
$E_{\text{bb\_dsp}}$	2×28.7	2×474.4	2×10.5	2×374.8

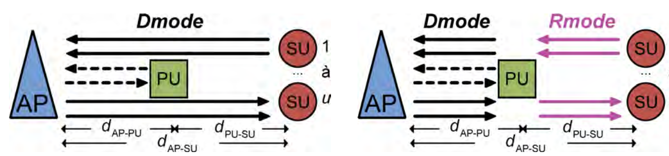
A. Energy properties of the terminals

This work focuses on 802.11g at 6 Mbps and 802.15.4 at 20 kbps. Each mode can use one or multiple antennas transmission and reception ($N^{[\text{TX,RX}]}$). E_{num} is evaluated for given numerical complexities [7] and an ARM 968E-S processor [6]. E_{rf} depends on the specification of two radio front-ends: an adaptive front-end in 802.11 [4], and simpler architecture in 802.15.4 [5]. Table I sums up these values.

Table II shows the numerical complexity per bit for MIMO. We consider an Alamouti scheme in transmission, and an MMSE algorithm in reception. From (2), Table III evaluates the numerical energy consumption to transmit/receive one data bit in the selected modes ($E_{\text{bb\_dsp}}$ depends on the number of antennas, and $E_{\text{combiner}} = 0$ in SISO). More details can be found in [2].

B. Simulated scenarios

The Access Point (AP), is a fixed terminal, connected to the Internet with no energy constraints. The user terminals are multi-mode SDR terminals with MIMO capacity. They have an energy limit. We consider Primary Users (PU) as mobile terminals which can relay Secondary Users (SU).



(a) S_{direct} (b) S_{relay}

Fig. 2. Schematic representation of the scenarios studied

Fig. 2 presents the two scenarios studied:

- S_{direct}: one PU and u SUs communicate with the AP.
- S_{relay}: one PU relays u SUs on dedicated connections.

Here, the PU moves from the AP toward the SUs, placed on a circle at $d_{\text{AP}-\text{SU}} = 30$ m. We distinguish *Dmode*, the communication mode between all mobile users and the AP, and *Rmode* the communication mode used the relay link. Here, *Dmode* is 802.11g at 6 Mbps. P_{out} is adapted to the channel path-loss (PL) and the receiver sensivity ($RXSens$). Moreover, P_{out} is distributed on all antennas, so that it remains identical in SISO and in MIMO. Table I sums up these parameters and the channel models (with an independent Rayleigh fading applied to each channel).

C. Simulation environment

We choose WSNet, a discrete event network simulator to evaluate the energy consumption of the different scenarios. In MIMO, the transmitted frames are duplicated on N^{TX} antennas after coding. In reception, each antenna receives N^{RX} packet. For a given mode, transmission and reception use the same number of antennas ($N^{\text{TX}} = N^{\text{RX}}$).

The MAC layer is CSMA/CA in 802.11g (with control packets) and CSMA with no control packets in 802.15.4. Retransmission is triggered regarding to the *Signal to*

Noise Ratio (SNR), which is evaluated as the average SNR of the combined packets.

D. Simulation results

In the presented results, we consider packet retransmissions and no external interference. Moreover, all relays follow a Decode and Forward scheme.

We now evaluate E_{global} for S_{direct}, for S_{relay} in multi-mode (*Rmode* is 802.15.4 at 20 kbps), and for S_{relay} in mono-mode (*Rmode* is 802.11g at 6 Mbps), in SISO and MIMO. We send $b_0 = 500$ bytes at each round of the simulation. Hence, E_{global} represents the average energy consumption of the network.

Fig. 3 shows that for $u = 1$ SU. For PU close to AP ($d_{\text{AP-PU}} < 15$ m), S_{relay} in SISO has the lowest energy consumption of all scenarios (the consumption of the 802.15.4 is lower than 802.11g). At long range, S_{direct} is more interesting because the SU receives data on the 802.11g interface: this passive overhearing leads to a higher energy consumption in S_{relay}. Additionally, passive overhearing is higher in MIMO because of the higher *RXSens*.

E. Different solutions to reduce passive overhearing

We propose two solutions to minimize the impact of passive overhearing in MIMO communications : 1) *MISO passive overhearing*: a terminal listens to the channel using only one antenna. It activates multiple antennas to communicate. The energy consumption due to passive overhearing is minimized for MISO terminals. 2) *Deactivated passive interface*: we deactivate the 802.11g interface for all SUs (they behave like 802.15.4-only terminals). This strategy removes all passive overhearing of 802.11g by the SUs. It is combined with strategy 1.

Fig. 4 and Fig. 5 evaluate the impact of each strategy on E_{global} for the presented scenarios. Fig. 4 shows that MISO is interesting compared to unrestricted MIMO but passive overhearing still occurs at the inactive interface at long distance. Fig. 5 shows that deactivating the SUs' 802.11g interface removes all passive overhearing in both SISO and MIMO links. Moreover, E_{global} is halved for S_{relay} compared to S_{direct}. This combination also shows an improvement in the energy consumption over a classical relay, with an E_{global} up to three times higher when the PU is far from the AP.

IV. Conclusion

In this paper, we have presented a multi-mode and MIMO terminal as a potential solution to minimize the global energy consumption. We have considered the MAC layer to propose a realistic energy model applied to multi-mode SDR terminals with MIMO capabilities. Network simulations shows that the energy performance of MIMO applied to multi-mode relays may bring important energy reduction when deactivating the passive interface.

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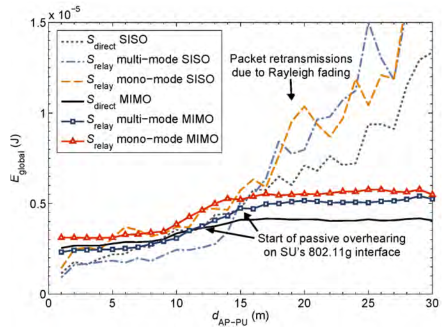

Fig. 3. Comparison of E_{global} for the scenarios ($u = 1$ SU)

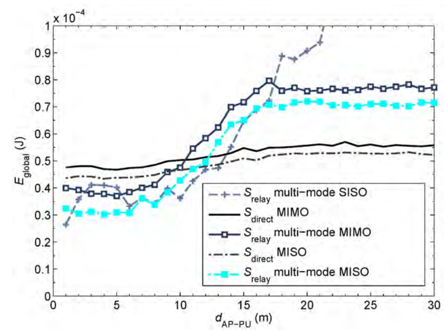

Fig. 4. E_{global} for *MISO passive overhearing* strategy ($u = 5$ SUs)

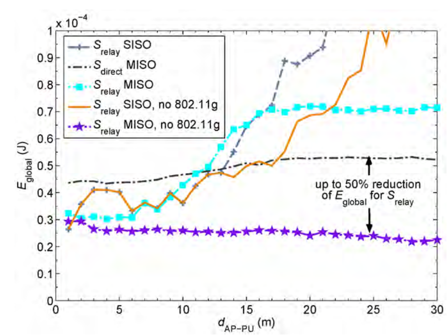

Fig. 5. E_{global} for SU's 802.11g interface deactivated ($u = 5$ SUs)