Power Consumption Optimization in Multi-mode Mobile Relay

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***Abstract*—Multi-mode is a common feature in current generation terminals, enabling the user to stay connected at any time. By selecting an appropriate standard, multi-mode can reduce terminal power consumption. Software Defined Radio is an enabler towards multi-mode for the next generation of terminals. In such a radio, communication modes are implemented by a general processor through digital functions, instead of dedicated chips. Providing access to users in bad conditions through relays, is another solution to reduce power consumption. We look at multi-mode relaying, where a mobile terminal, connected to an UMTS base station, acts as an 802.11g-relay for those users. In this paper, we evaluate the algorithmic complexity of 802.11g and UMTS to estimate the power consumption of a Software Defined Radio. We propose a multi-mode relay scheme using such terminals, with the purpose of minimizing the global power consumption. Finally, we enounce different rules to maximize the local and global power gain by implementing multi-mode relays.**

I. Introduction

Multi-mode is a key feature in all current mobile terminals. By enabling communication on different standards, such as UMTS or 802.11g, this property is a big step towards the unlimited connectivity requested by more users everyday. In Software Defined Radio (SDR), the increasing number of chips in current terminals is replaced by a single generic purpose processor running algorithms. Thus, a multi-mode SDR implements different standards as different algorithms. It brings the flexibility needed to guarantee an always available connection, while providing an adaptive and reconfigurable terminal. This reconfiguration is at the center of the IEEE SCC41 Working Group [1], via P1900.4 [2].

Still, another problem remains. How can operators ensure an all time connectivity, without generating new costs? Relay usage is one possible answer. A relay is a device transmitting data from users in bad conditions to a base station. Such relays can be deployed by operators or be mobile, where users' terminals act as potential relays. Relaying enables a better efficiency on network coverage [3], a greater capacity [4] and reduces the transmission power [5]. Their implementation increases the network lifetime.

The decision for a terminal whether to act as a relay or to be relayed depends on a metric: for example transmission power reduction based on the channel conditions [6], or network capacity improvement [7]. Metrics are computed either locally by the terminal [8], or globally by the operator [9].

In our work, we consider mobile multi-mode relays: a terminal communicating with other users on one standard, and with the base station on another standard. Since mobile terminals are power-limited, we reduce the power consumption by taking advantage of multi-mode. Contrary to classical works in the relaying field, we focus on the physical layer power consumption, including not only the transmission power but also numerical and analogical power consumptions. The scope of this paper is the physical layer power consumption, and thus, we do not consider upper layers.

A SDR is a convenient way to implement multi-mode. Even though its power consumption is beyond classical radios, this drawback is largely compensated through reconfiguration, which allows the terminal to change mode following different criteria. Current works refer to channel conditions [10]. We propose a new reconfiguration scheme based on power reduction. In order to evaluate a terminal power consumption for every mode, we separate the numerical power consumption (linked to the algorithmic complexity), and the radio power consumption (depending on the radio front-end and transmission power). Then, we compare all modes and reconfigure the terminal to the most power efficient one. Hence, the terminal power consumption is minimized at all time.

We detail the previous stages in Section II. Then, we compare a multi-mode relay with direct connections in order to reduce the network global power consumption in Section III. Finally, we express rules to minimize the global power consumption using a mobile multi-mode relay in Section IV.

II. Towards a lower power consumption

In Software Defined Radios (SDR), a physical layer is implemented through algorithms. Being multi-mode, the radio runs the different algorithms corresponding to the selected modes at the same time. We propose to communicate on the mode minimizing the SDR power consumption, which is composed of two parts: the numerical power consumption, and the radio power consumption.

TABLE I
ALGORITHMIC COMPLEXITY (OPERATIONS PER BIT)

802.11g	24 Mbps	36 Mbps	48 Mbps	54 Mbps
TX	102	123	114	121
RX	270	291	282	289

UMTS	32 kbps	64 kbps	384 kbps
TX	1,320	1080	745
RX	11,438	7,075	3,531

A. Algorithmic complexity evaluation

In order to evaluate the numerical power consumption, we compute the algorithmic complexity per bit for every mode, by refering to Neel, Robert and Reed's work [11]. This complexity per bit allows us to compare different standards.

We present the *number of operations per bit* for each mode (rounded to the upper integer) in IEEE 802.11g and UMTS (Table I). For a more detailed version, please refer to [12].

B. Numerical power consumption

Once we know the algorithmic complexities, we evaluate the numerical power consumption, P_p (in Watt), following [13]:

$$P_p = N * C * V_{dd}^2 \quad (1)$$

with N being the number of cycles, C the processor's switching capacitance (in Farad) and V_{dd} the input voltage (in Volt). For a given processor, at fixed frequency, the number of cycles increases with the algorithmic complexity. This leads to a higher power consumption. Considering an ARM ARM 968E-S, we have $V_{dd} = 1.2$V and $C = 97.3$pF.

In order to express P_p in Watt per bit, we consider one operation per bit and set N to the number of operations per bit evaluated before. This result gives us the power required to transmit or receive one single data bit in the chosen mode. We call it the *power cost per bit*.

C. Radio power consumption

We separate the radio power consumption into two parts: the radio-frequency front-end power consumption, and the transmission power. We consider a multi-mode radio-frequency front-end, capable of receiving simultaneously an 802.11g and an UMTS signals, as presented in [14]. The front-end power consumption depends on the architecture and the activity (in transmission or reception). We evaluate the radio power consumption, P_c (in Watt), using [15]:

$$P_c = N_T T_{on}[P_{te} + P_O] + N_R R_{on} P_{re} \quad (2)$$

with P_{te} and P_{re} (in Watt) being the power consumption of the front-end components, respectively when emitting and receiving, P_O the output signal power (in Watt), T_{on} and R_{on} defining transmission or reception, and N_T and N_R the amount of time the transmitter/receiver is switched on per period. Since a radio can either transmit or receive a signal at a given moment, for $T_{on} = 1$, $N_T = 1$ and $N_R = 0$; reciprocally for $R_{on} = 1$. We evaluate the power consumption during a single data bit and express P_c in Watt per bit.

Yet, P_O must be taken into account in transmission, since it depends on the channel conditions and the distance with the receiver. We explain how to evaluate P_O in Section III-B.

Those hypothesis allow us to express the *power cost per bit* for all modes of our SDR on Fig. 1.

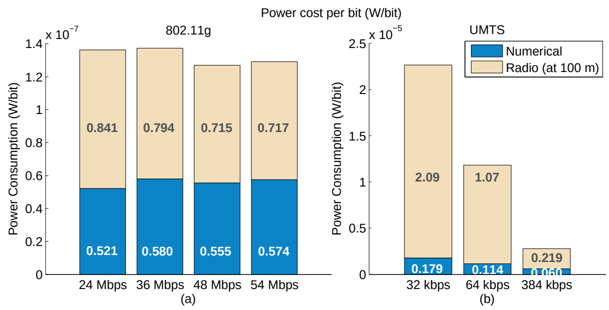

Fig. 1. Power cost per bit (W/bit) in (a) 802.11g (b) UMTS. For the radio part, the distance between the emitter and the receiver is 100 m.

In 802.11g, the numerical and radio power are almost identical to transmit and receive one data bit (Fig. 1a). The radio power mostly depends on the transmission power, adjusted according to the receiver's channel conditions.

In UMTS, the numerical and radio power decrease at high data rate, due to reduced complexity and sampling. Moreover, the numerical power represents approximately a quarter of the radio power at 384 kbps (Fig. 1b).

By taking into account those results, the fastest rate is not always the most power consuming. Thus, we use the fastest mode to reduce the power cost per bit.

III. REDUCTION OF THE GLOBAL POWER CONSUMPTION

A. Case Comparison

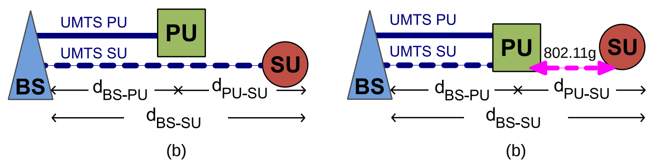

Fig. 2. (a) Two terminals are directly connected to an UMTS Base Station (BS). (b) A Secondary User (SU) connects to a Primary User (PU) in 802.11g. The latter establishes a secondary UMTS connection to transmit SU data.

We consider an UMTS Base Station (BS) and two SDR terminals, one is a Primary User (PU) capable of becoming relay, the other is a Secondary User (SU). The terminals communicate at 54 Mbps in 802.11g with each other and at 384 kbps in UMTS with BS.

We define the *global power consumption* as the sum of all terminals' power cost per bit. We compare the global power consumption, in Watt per bit, for the following cases:

1) PU_{direct}: PU and SU communicate directly in UMTS with BS (Fig. 2a).
2) PU^{active}_{relay}: PU communicates in UMTS with BS and acts as a relay. SU's signal is relayed in 802.11g on another UMTS connection establised by PU (Fig. 2b).

3) $\text{PU}_{relay}^{inactive}$: PU is not in communication and acts as a relay. SU's signal is relayed in 802.11g on the UMTS connection established by PU. This case can also represent PU sharing its own connection, via multiplexing or aggregation techniques for example.

B. Channel conditions

The terminals control their transmission power by reducing P_O to the minimum value allowing the receiver to decode data properly. The required radio power to transmit a single bit is obtained by integrating P_O in (2).

Since, P_O depends on the channel conditions, we model the 802.11g and UMTS channels independently. We use an ITU-R office indoor channel model for 802.11g [16]:

$$L = 20log_{10}(f) + 30log_{10}(d) - 28 + L_f(n) \tag{3}$$

with L being the pathloss (in dB), f the carrier frequency (in MHz), d the distance between two terminals (in m), 28 the freespace loss coefficient and $L_f(n)$ the floor penetration loss factor with n the number of floors penetrated. Here, $L_f(n) = 15 + 4(n-1)$ for $n = 2$.

We use the following Outdoor-to-Indoor empirical channel model in UMTS [17]:

$$\begin{aligned} L_{in,LOS,K} &= 32.4 + 20log_{10}(f) + 20log_{10}(S + d_{in}) \\ &\quad + L_{perp} + L_{par}(1 - \frac{D}{S})^2 \end{aligned} \tag{4}$$

with $L_{in,LOS,K}$ the pathloss with line of sight (in dB), f the carrier frequency (in MHz), d_{in} the distance between the terminal and the outdoor (in m), S and D the distances between the base station and the building (in m), respectively in line of sight and parallel to the ground, L_{perp} and L_{par} the wave penetration factors into the building (in dB), respectively for a perpendicular incidence and the line of sight angle. We take $L_{perp} = 10\text{dB}$, $L_{par} = 40\text{dB}$, $\frac{D}{S} = 0.4$, and the mobile terminal inside the building, $d_{in} = 10\text{m}$ from the walls.

We apply a Rice fading to both signals, since the terminals are in line of sight.

C. Mobile relay

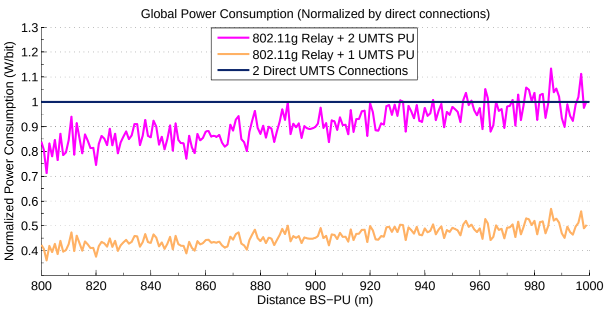

Fig. 3. Global Power Consumption in Watt per bit (Normalized by direct connections) with a Primary User (PU) acting as a mobile relay for a fixed Secondary User (SU).

PU moves in straight line from $d_{BS-PU} = 800\text{m}$ to SU, fixed at distance $d_{BS-SU} = 1,000\text{m}$. We compare the global power consumption for all three previous cases on Fig. 3.

When PU and SU are far from each other, $\text{PU}_{relay}^{active}$ is more efficient than direct connections. However, when PU is getting closer to SU, relaying becomes more expensive: the power cost per bit of two UMTS connection plus an 802.11g relay is approximately the same as two direct UMTS connections. At that point (30m$< d_{PU-SU} <$ 80m), PU enters a "No-Relay Zone": a zone where relaying has no major gain compared to direct connections. When PU and SU are too close ($d_{PU-SU} <$ 30m), direct connections should to be privileged.

We also notice that $\text{PU}_{relay}^{inactive}$ always gives the lowest global power consumption. This behaviour comes from the highest power cost per bit in UMTS: when PU and SU become closer, PU only maintains one UMTS connection and an 802.11g link for the relay. Compared to two UMTS connections at long range, and due to the fact that the power cost per bit is much lower in 802.11g than in UMTS, the global power consumption is minimized when PU shares its UMTS connection.

D. Fixed relay

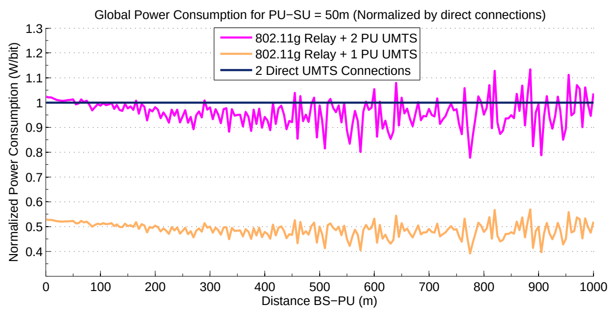

Fig. 4. Global Power Consumption in Watt per bit (Normalized by direct connections) with a Primary User (PU) acting as a fixed relay for a Secondary User (SU) at 50m. PU and SU move away together from the base station. The results for direct connections and $\text{PU}_{relay}^{active}$ overlap each other.

PU and SU move together in straight line from BS to $d_{BS-PU} = 1,000\text{m}$. We fix $d_{PU-SU} = 50\text{m}$ to study the persistence of the "No-Relay Zone", at any distance from BS. The global power consumption is depicted on Fig. 4.

Near BS, $\text{PU}_{relay}^{active}$ is not interesting. For 200m$< d_{BS-PU} <$ 300m, the gain is neglectable. Far from BS, direct connections are privileged. Meanwhile, $\text{PU}_{relay}^{inactive}$ is always interesting for the same reason as above.

E. Multi-users mobile relay

We now evaluate the gain of relaying N SUs on $\text{PU}_{relay}^{active}$, with PU moving in straight line from $d_{BS-PU} = 800\text{m}$ to $d_{BS-SU} = 1,000\text{m}$ on 5. With PU far from SU, the global power consumption of N SUs directly connected in UMTS is approximately the same as PU relaying $N+2$ SUs. When PU gets closer to SU, direct connections become more efficient. Moreover, $\text{PU}_{relay}^{inactive}$ is always interesting.

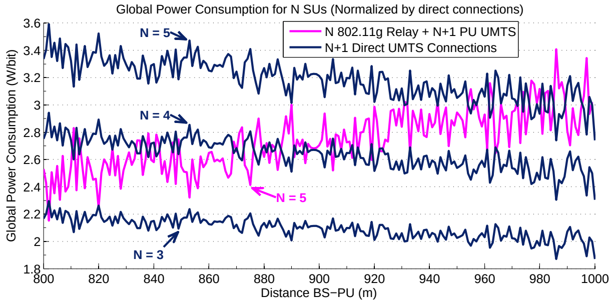

Fig. 5. Global Power Consumption in Watt per bit (Normalized by direct connections) with a Primary User (PU) acting as a mobile relay for N fixed Secondary User (SU). PU maintains $N+1$ UMTS connections with the base station (N SUs and its own).

IV. Discussion

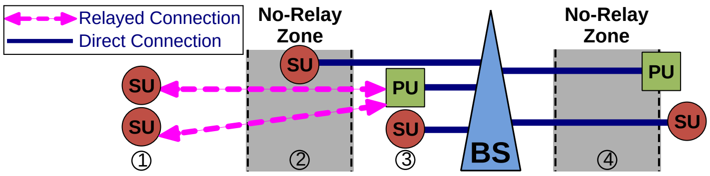

Fig. 6. The different relay rules depend on the position of Primary Users (PU) and Secondary Users (SU).

Based on the previous results, the following rules allow to minimize the global power consumption (Fig. 6).

- Terminals far from BS are relayed by PU closer to BS (Fig. 6 ①, ③).
- In the "No-Relay Zone", a terminal relaying has no impact on the global power consumption. Terminals connect directly to BS in UMTS (Fig. 6 ②).
- When PU and SU are too close from each other, they contact BS directly (Fig. 6 ③, ④).
- For multi-users, PU shares its connections when approaching SUs (Fig. 6 ①).

All other approaches aiming at power reduction only consider the transmission power and forget the numerical power consumption. We have shown how important the numerical power consumption is in multi-mode, and have minimized the global power consumption using multi-mode relay.

By adding mobility, the terminal acting as a PU will relay for a certain period, before entering the "No-Relay Zone". At that moment, PU stops relaying. Later, that terminal can become a new SU and be relayed by a new PU. This way, by reducing a terminal power consumption, we minimize the global power consumption.

V. Conclusion and Future Work

In this paper, we have shown how to minimize a network global power consumption by using a Software Defined Radio as a multi-mode mobile relay. We have expressed the need to evaluate a terminal power consumption, and have calculated the complexity of two standards and their associated power cost per bit. We have determined the gain provided by such terminal, acting as a multi-mode mobile relay, on the global power consumption. Finally, we have presented different rules to establish a relay in order to reduce the global power consumption.

We will continue to explore this reconfiguration scheme in a multicast streaming network and study the benefits for operators and users at the same time. We will also study the minimization of power consumption with mobile SUs and multiple relays, and evaluate the impact of a realistic MAC layer using network simulation.

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