This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2009 proceedings

Low Bound of Energy-Latency Trade-off of Opportunistic Routing in Multi-hop Networks

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***Abstract*—During the last decade, many works were devoted to improving the performance of relaying techniques in *ad hoc* networks. One promising approach consists in allowing the relay nodes to cooperate, thus using spatial diversity to increase the capacity of the system. However, this approach introduces an overhead in terms of information exchange, increasing the complexity of the receivers. A simpler way of exploiting spatial diversity is referred to as opportunistic routing. In this scheme, a cluster of nodes still serves as relay candidates but only a single node in the cluster forwards the packet. This paper proposes a thorough analysis of opportunistic routing efficiency under different realistic radio channel conditions. The study aims at finding the best trade-off between two objectives: energy and latency minimizations, under a hard reliability constraint. We derive an optimal bound, namely, the Pareto front of the related optimization problem, which offers a good insight into the benefits of opportunistic routing compared with classical multi-hop routing.**

I. Introduction

Channel fading was traditionally considered as a source of unreliability that has to be mitigated in wireless networks. However, information theory in [1] reveals that channel fluctuations can be rather beneficial if strong channel states are opportunistically exploited. To achieve the full capacity of such a system, the relaying nodes should cooperate to form a virtual Multiple Input Multiple Output (MIMO) system [2]. Although it is theoretically efficient, the requirements of synchronization and local data exchange [3] make the transmission protocols more complex, which finally reduces the advantage of capacity.

As a consequence, exploiting the spatial diversity in a more efficient way is attractive. It is exactly the purpose of opportunistic routing techniques, e.g., [4], [5]. Compared with traditional point-to-point (P2P) multi-hop routing, the basic idea of opportunistic routing is that, at each hop, a set of next-hop relay candidates receiving a packet successfully compete for acting as relay. For relay selection, a priority is assigned to each relay candidate according to a specified metric, for example, the geographical *closeness* of the relay candidate to the destination [4].

The aim of this paper is to evaluate the maximal efficiency that can be achieved with such opportunistic routing. The efficiency of opportunistic communications can be evaluated from different points of view. For multi-hop networks, we identify three important performance parameters: the end-to-end reliability, the end-to-end delay (refereed to as latency in the following) and the energy consumption. Thus, choosing an efficient routing scheme is a multi-objective optimization problem [6]. Due to the fundamentality of reliability, we consider it in this paper as a hard constraint. The use of acknowledged transmissions is to fulfill this constraint, at least from a theoretical point of view. The other two constraints, i.e., energy and latency, are considered as two competing objective functions that should be simultaneously minimized. Note that we do not address the problem of the relay selection policy in this paper.

Several previous works on opportunistic routing, such as [4], [7]–[10], provide the analyses of energy and latency performances. In [4], [7], energy and latency performances of a routing scheme called *GeRaF* are analyzed, and the effects of node density, traffic load and duty cycle are evaluated. The simulations in [8] show the impacts of node density, radio channel quality and traffic rate on the energy consumption at each node, the average delay of packet and the goodput of opportunistic protocol. It is concluded that the benefit of opportunistic scheme is about 10% decrease in power and 40% reduction in delay. Whereas these analyses are based on an unrealistic disc link model [11], [12] which relies on the definition of a reception threshold level and is not well adapted to the research of opportunistic communications due to the neglect of propagation phenomena, e.g., fading and shadowing. Furthermore, the energy efficiency of the protocol CAGIF [9] is studied in a fading channel, where the whole set of neighbor nodes try to receive the packet from the source node. While in [10], an efficient selection mechanism of relay nodes is proposed, instead of choosing the whole neighbors as relay candidates, in order to optimize energy efficiency. Simulations of [10] in a shadowing channel indicate that the energy efficiency is greatly improved.

However, in aforementioned studies, a fixed transmission power is considered and the number of relay candidates is chosen according to a given routing policy, without providing any proof of optimality. Therefore, these studies are insufficient to determine whether the relative low performances of opportunistic routing are intrinsic to this kind of routing or due to the specific protocol (relay selection policy, fixed power choice, etc.).

Concerning this question, we propose in this paper to calculate the low bound of the energy-latency trade-off for opportunistic communications under a hard end-to-end relia-

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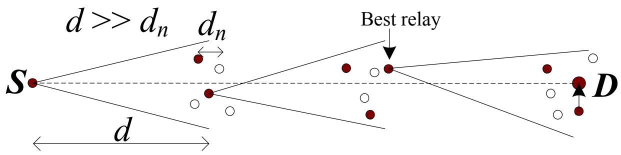

Fig. 1. Scheme of 'Best relay'

bility constraint. To compute this bound, we consider the size of candidate cluster and the transmission power as variables of the optimization problem. As stated previously, we do not focus on the relay selection mechanism here but the two following questions: what is the best set of relay candidates and what is the performance of the optimized set of candidates?

With regard to the routing policy, we assume that for a given cluster, only the candidate closest to the destination is selected to forward the packet. Such a strategy obviously relies on the assumption that each node has the full knowledge of the position of itself and the destination. Once a node has a packet to send, it appends the locations of itself and the intended relay cluster to the packet, then broadcasts it. The relay candidates which successfully receive the packet (solid nodes in Fig. 1) assess their own priorities of acting as relay, based on how close they are to the destination. The *best relay* which is the closest to the destination relays the packet, as shown in Fig. 1. In contrast with the the aforementioned schemes, this scheme utilizes an optimized candidate cluster, instead of all the active neighbors, to receive the packet for the purpose of saving energy and taking advantage of the spatial diversity.

The main contributions of this paper are:

- A general framework for evaluating the maximal efficiency of the opportunistic routing principle is provided. Energy and latency are compromised under an end-to-end reliability constraint.
- The Pareto front of energy-latency trade-off is derived numerically for different scenarios. The numerical analyses show that opportunistic routing is inefficient in Additive White Gaussian Noise (AWGN) channel, in reverse, is efficient in Rayleigh block fading channel on the condition of a small size cluster.

The paper is organized as follows: Section II describes the utilized models and metrics. In Section III, the energy minimization is assessed with respect to the size of relaying cluster, the transmission power and the one-hop transmission distance in AWGN channel and Rayleigh block fading channel. In section IV, the above issue is further studied as a trade-off between energy and latency, and the performance of opportunistic routing is discussed. Section V discusses the effects of these results and gives some conclusions.

II. Models and Metric

In this section, we introduce the energy and latency models, the realistic link model and the metric $\overline{EDRb}$ used in this work. The cluster size of relay candidates is given by N_R. It is assumed that the distance between receivers within a cluster d_n is much smaller than that between the source and the cluster d, i.e., $d \gg d_n$ as shown in Fig. 1. Thus, all the relay candidates in a cluster are assumed to be at the same distance from the source.

TABLE I
Numerical values for the parameters of the transceivers [14]

Symbol	Description	Value
P_{start}	Startup power	$58.7\ mW$
T_{start}	Startup time	$446\ \mu s$
β_{amp}	Amplifier proportional offset (>1)	5.0
P_{Elec}	Circuitry power	$279\ mW$
N_b	Number of bits per packet	2560
R	Transmission bit rate	$1\ Mbps$
N_0	Noise level	$-154 dBm/Hz$
f_c	Carrier frequency	$2.4GHz$
G_{Tant}	Transmitter antenna gain	1
G_{Rant}	Receiver antenna gain	1
α	Path-loss exponent	3
L	Circuitry loss	1
τ_{ack}	ACK coefficient	0

A. Energy consumption model

According to the previous assumptions, the energy consumption for transmitting one packet E_p is composed of three parts[1]: the energy consumed by the transmitter E_{Tx}, by the receiver E_{Rx} and by the acknowledgement packet exchange E_{ACK}:

$$E_p = E_{Tx} + N_R \cdot E_{Rx} + E_{ACK}, \tag{1}$$

where N_R is the number of receivers in a cluster. Concerning E_{Tx} and E_{Rx}, refer to (2) and (3) in [13].

With respect to the acknowledgement process, we assume it has the similar transmission scheme to the one of a data packet. The minimal energy expenditure for acknowledgement is thus given by:

$$E_{ACK} = \tau_{ack}(N_R E_{Rx} + E_{Tx}), \tag{2}$$

where τ_{ack} represents the ratio of size between ACK packet and data packet. We assume that ACK packet is much smaller than data packet [13], i.e., $0 \leq \tau_{ack} \leq 1$. Since we are interested to find a low bound of energy consumption, τ_{ack} is set as 0 in the following.

Therefore, the energy consumption per bit is:

$$E_b = \frac{E_p}{N_b} = (1+\tau_{ack})((N_R+1)\cdot E_c + K_1 \cdot P_t) \tag{3}$$

where P_t is the transmission power. Here, $K_1 \cdot P_t$ stands for the radio emission energy and E_c denotes the circuit energy per node, which are obtained by:

$$E_c = \frac{T_{start}\cdot P_{start}}{N_b} + \frac{P_{Elec}}{R},\ K_1 = \frac{\beta_{amp}}{R}.$$

The related parameters are described in Table I.

[1]For the sake of simplification, channel coding is not considered in this work. The energy cost for coding/decoding is then set as zero.

B. Realistic unreliable link models

As claimed in the introduction, it is very crucial to take transmission errors into account to ensure a reliable transmission. Hence, we consider herein a radio link probability which is derived from the packet error rate (PER) according to [13]:

$$pl(\gamma_{x,x'}) = 1 - PER(\gamma_{x,x'}), \quad (4)$$

where $PER(\gamma)$ is the PER obtained for a signal to noise ratio (SNR) γ. The PER may have various forms depending on the transmission technology (modulation, coding, diversity ...). $\gamma_{x,x'}$ is derived from the classical attenuation model in [14]:

$$\gamma_{x,x'} = K_2 \cdot P_t \cdot d_{x,x'}^{-\alpha}, \text{ with } K_2 = \frac{G_{Tant} \cdot G_{Rant} \cdot \lambda^2}{(4\pi)^2 N_0 \cdot B \cdot L}, \quad (5)$$

where $d_{x,x'}$ is the transmission distance between nodes x and x', B is the bandwidth of channel and is set as $B = R$, λ is the wavelength (*cf.* Table I for other parameters).

In the following, we consider the scenario of Binary Phase Shift Keying (BPSK) modulation and coherent detection. The unreliable link models are then approximated for AWGN and Rayleigh block fading channels respectively as follows (refer to [13] for more details):

$$pl_g = (1-0.1826\alpha_m \cdot \exp(-0.5415\beta_m\gamma_b))^{N_b}, \text{ if } \beta_m \cdot \gamma_b \geq 2, \quad (6)$$

$$pl_b(\overline{\gamma}) = \exp\left(\frac{-4.25 \lg N_b + 2.2}{\beta_m \overline{\gamma}}\right), \text{ when } \alpha_m = 1, \quad (7)$$

where α_m and β_m rely on the modulation type and order [15]. For BPSK, $\alpha_m = 1$ and $\beta_m = 2$.

According to the opportunistic relaying principle, the successful transmission means that at least one node receives the packet correctly. Therefore, the probability of a successful transmission is:

$$p_s = 1 - (1 - pl(d, P_t))^{N_R}. \quad (8)$$

C. mean Energy Distance Ratio per bit ($\overline{EDRb}$)

To evaluate the energy efficiency, we adopt the metric: mean Energy Distance Ratio per bit ($\overline{EDRb}$), because it integrates all factors of physical and link layers.

According to the definition of $\overline{EDRb}$, we have:

$$\overline{EDRb} = \frac{E_b(P_t) \cdot \overline{N}_{retx}}{d}. \quad (9)$$

Here, $\overline{N}_{retx}$ is the average number of retransmissions:

$$\overline{N}_{retx} = \sum_{n=1}^{\infty} n \cdot p_s(d, P_t) \cdot (1 - p_s(d, P_t))^{(n-1)} = \frac{1}{p_s(d, P_t)}, \quad (10)$$

where n is the number of packet transmissions, including retransmissions. It should be noticed that this metric integrates all factors of physical and link layers.

D. Latency model

The average latency for a packet to be transmitted over one hop, D_{onehop}, is defined as the sum of three delaying components. The first component is the queuing delay during which a packet awaits to be transmitted. The second component is the transmission delay that is equal to N_b/R. The third component is T_{ACK}, the time slot during which all nodes wait and receive ACK reply. Note that we neglect the propagation delay because the transmission distance between two nodes is usually short in multi-hop networks. Without loss of generality, for a fixed packet size, D_{onehop} is set to be 1 unit.

However, the one-hop delay varies from one link to another due to retransmissions. According to (10), the expected latency of a reliable one-hop transmission is:

$$\overline{D} = D_{onehop} \cdot \overline{N}_{retx} = \frac{1}{p_s(d, P_t)}. \quad (11)$$

III. ENERGY MINIMIZATION FOR ONE-HOP TRANSMISSION

In this section, the energy consumption is evaluated and minimized for one-hop transmission from a source to a cluster of N_R relay candidates. Then the results are extended to the case of multi-hop transmissions. We derive the optimal transmission power and the optimal relaying cluster size in AWGN and Rayleigh block fading channels.

The optimization of the energy efficiency can be abstracted as a mixed integer nonlinear programming (MILNP) problem:

$$\begin{aligned} &\text{Minimize}: \ \overline{EDRb} \\ &\text{Subject to}: \ P_t > 0, d > 0, N_R \geq 1, \ N_R \in \text{Integer}. \end{aligned} \quad (12)$$

A. Optimal transmission power

Assuming N_R constant and according to the approach detailed in [13], the optimal transmission power is obtained by deriving $\overline{EDRb}$:

$$\frac{\partial \overline{EDRb}}{\partial P_t} = \frac{\partial}{\partial P_t}\left(\frac{E_b(P_t)}{d \cdot p_s(d, P_t)}\right)\Bigg|_{P_t = P_0} = 0 \quad (13)$$

$$\frac{\partial \overline{EDRb}}{\partial d} = \frac{\partial}{\partial d}\left(\frac{E_b(P_t)}{d \cdot p_s(d, P_t)}\right)\Bigg|_{d = d_0} = 0. \quad (14)$$

Substituting (8) into (13) and (14) and solving this set of equations, according to the derivation detailed in [13], we obtained:

$$P_0 = \frac{(1 + \tau_{ack})(N_R + 1)E_c}{K_1(\alpha - 1)}. \quad (15)$$

We note that the stronger the attenuation slope α is, the lower the optimal power P_0 is, that is to say, more hops are needed for a given distance, resulting in a higher latency.

Substituting (8) and (15) into (9) respectively, we derive the optimal $\overline{EDRb}$:

$$\overline{EDRb}_0(d) = \frac{2(1 + \tau_{ack})(N_R + 1)E_c}{d(\alpha - 1)(1 - (1 - pl(d, P_0))^{N_R})} \quad (16)$$

where pl stands for either pl_g or pl_b.

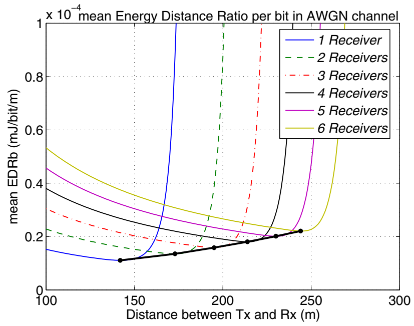

Fig. 2. $\overline{EDRb}$ in AWGN channel with $\alpha = 3$. For this example, the minimal $\overline{EDRb}$ is reached with relaying cluster size $N_R = 1$, one-hop length $d_0 = 142m$ and transmission power $P_0 = 79.21mW$. At the lowest point, the radio link probability is $p_s = 0.96$.

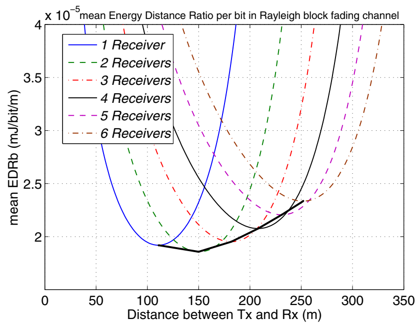

Fig. 3. $\overline{EDRb}$ in Rayleigh block fading channel. For this example, the minimal $\overline{EDRb}$ is reached with relaying cluster size $N_R = 2$, $d_0 = 151m$ and $P_0 = 152.30mW$. At the lowest point, the radio link probability is $p_s = 0.83$.

B. Optimal distance versus cluster size

Fig. 2 plots $\overline{EDRb}$ for AWGN channel as a function of the one-hop distance d_0 for different cluster sizes. Firstly, considering the curve corresponding to $N_R = 1$, we observe that an optimal distance can be found which corresponds to the best trade-off between radiation and circuitry energy expenditure. In addition, the larger the cluster size is, the longer the one-hop optimal distance is (note that the transmission power is optimized for each distance, according to (15)). However, the optimal $\overline{EDRb}$ increases monotonically with the cluster size, which means that the optimal configuration to achieve global energy minimization is $N_R = 1$ for AWGN channel.

Fig. 3 shows the same results for Rayleigh block fading channel. In this case, the optimal cluster size is 2. The benefit of opportunistic communication in terms of energy efficiency, as shown in Fig. 4, is measured with the energy gain defined as:

$$Gain = \frac{\overline{EDRb}_{p2p} - \overline{EDRb}_{opp}}{\overline{EDRb}_{p2p}}. \qquad (17)$$

where the $\overline{EDRb}_{p2p}$ is the optimal $\overline{EDRb}$ for traditional point-to-point communications obtained by the approach presented in [13], and $\overline{EDRb}_{opp}$ is referred to as the optimal $\overline{EDRb}$ using opportunistic communications.

It should be noted that the gain diminishes with the increase

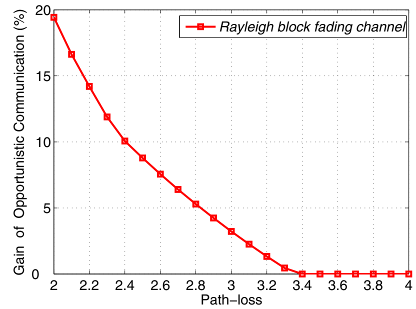

Fig. 4. Gain of opportunistic communication in Rayleigh block fading channel

TABLE II
OPTIMAL PARAMETERS (N_R, d) FOR DIFFERENT PATH-LOSS

Optimal parameters (N_R, d)	$\alpha = 2$	$\alpha = 3$	$\alpha = 4$
AWGN channel	$(1, 2500m)$	$(1, 142m)$	$(1, 37m)$
Rayleigh block fading channel	$(4, 4663m)$	$(2, 151m)$	$(1, 29m)$

of α, reaching zero when $\alpha \geq 3.4$. The opportunistic scheme improves the energy efficiency in unreliable channels on the condition of a small size cluster. Actually, the temporal diversity introduced by the retransmission process seems to be more efficient when $\alpha \geq 3.4$.

The optimal cluster size in different scenarios is given in Table II, together with the optimal one-hop distance defined in (12) (other parameters are provided in Table I).

These results reveal that the opportunistic routing is not efficient for AWGN channel, while it provides an optimal solution for Rayleigh block fading channel when the cluster size is small. Moreover, Fig. 2 and 3 show that the optimal one-hop distance increases with N_R. Therefore, in a multi-hop scenario, employing larger size clusters will result in a smaller number of hops, namely, a smaller latency. Consequently, we can deduce the energy of the system is minimized at the price of latency. We will concentrate on evaluating opportunistic routing in a multi-objective framework in the following.

IV. ENERGY-LATENCY TRADE-OFF

In this section, we analyze the energy-latency trade-off under the reliability constraint in the scenario that the distance between the source and the destination is fixed. Then, we derive the gain of opportunistic communication.

A. Energy-latency trade-off of one-hop transmission

Minimizing the energy consumption under a maximum delay constraint can be abstracted by the following problem:

$$\begin{aligned} \text{Minimize}: \quad & \overline{EDRb} \\ \text{Subject to}: \quad & P_t > 0,\ d > 0,\ delay \leq D, \\ & N_R \geq 1,\ N_R \in \text{Integer} \end{aligned} \qquad (18)$$

We employ the branch-and-bound algorithm [16] to solve this MINLP problem. To obtain the energy-latency trade-off

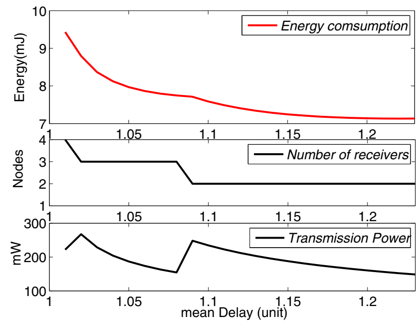

Fig. 5. Top: Energy-latency trade-off in Rayleigh block fading channel. Middle: Optimal values of N_R vs. latency. Bottom: Optimal transmission power vs. latency. Here, $d = 150m$, $\alpha = 3$, and other parameters are listed in Table I.

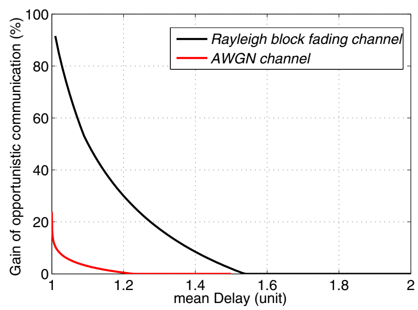

Fig. 6. Gain of opportunistic communications in Rayleigh block fading and AWGN channels obtained by Eq. (17). Here, the distance between the source and the destination is $150m$ for Rayleigh block fading channel and $300m$ for AWGN channel. $\alpha = 3$. *cf.* Table I for other related parameters.

curve, the maximum delay D is varied, and the corresponding optimal energy consumption is derived by solving this MINLP problem.

Fig. 5 shows the energy-latency trade-off in Rayleigh block fading channel. In this example, the lowest point of the curve represents the minimum energy consumption, and the corresponding optimal cluster size is 2. It is consistent with the numerical result in Fig. 3. At the left side of the curve, the minimum energy points are obtained when $N_R > 2$. In this case, the corresponding energy consumption increases, while the mean delay decreases since the link gets more and more reliable as a result of more relay candidates, i.e. experiences less retransmissions. This figure clearly shows the dependency of reliable transmission on both the spatial diversity and the temporal diversity as analyzed in Section III.

The gain of opportunistic communication: Without the delay constraint, the maximal energy gain of opportunistic communication is only 19% in Rayleigh fading channel, while 0% in AWGN channel as shown in Fig. 4. Subsequently, we analyze the energy gain of opportunistic communication under the delay constraint, compared with the traditional point-to-point communication according to Eq (17).

In Fig. 6, the gain of opportunistic routing versus the latency is compared for both channels. $\overline{EDRb}_{p2p}$ is obtained according to the approach proposed in [13]. In this example, the gain of opportunistic communications reaches 90% in Rayleigh block fading channel under the delay constraint. This value greatly outperforms the barely 19% of Fig. 4. In this kind of channel, we can conclude that opportunistic routing benefits from the effect of fading and improves the energy efficiency. Meanwhile, this gain is up to 20% for AWGN channel instead of 0% without the delay constraint.

B. Energy-latency trade-off of multi-hop transmission

The end-to-end transmission is consisted of two kinds of communications, as shown in Fig. 1: the first one is the point-to-point communication between the last relay node and the destination at the last hop since the last relay node is very close to the destination, and they can communicate with each other directly; the second one is the multi-hop opportunistic transmission before the P2P transmission. In this paper, we assume that the source is far from the destination. Therefore, in order to find the low bound of energy-latency trade-off for the end-to-end transmission, we neglect the energy and delay introduced by the last point-to-point hop because its contribution to the total energy expenditure and total delay is very small.

In order to obtain the low bound of energy-latency trade-off of multi-hop transmission, the theorems about *equivalent distance transmission* are introduced as follows:

Theorem 1: In an homogeneous network, a source node x sends a packet of N_b bits to a destination node x' using n hops in opportunistic communication mode. The n relaying clusters are located around (x, x') line, as shown in Fig. 1, and each cluster has the same number of relay candidates N_R. The distance between x and x' is d. The length of each hop is $d_1, d_2, \ldots, d_n$ respectively, and the average EDRb is denoted as $\overline{EDRb}(d)$. The minimum mean total energy consumption $\overline{Etot}_{min}$ is obtained if and only if $d_1 = d_2 = \ldots = d_n$:

$$\overline{Etot}_{min} = N_b \cdot \overline{EDRb}(d/n) \cdot d. \tag{19}$$

Proof: According to the method of [13], this theorem can be proved using the method of the Lagrange multipliers. This theorem is valid if and only if $\frac{\partial \overline{E}}{\partial d}$ is a monotonic increasing function of d which holds with the attenuation model in (5) in case of $\alpha \geq 2$ in many practical scenarios. The detailed proof is omitted because of the space limit. ∎

Theorem 2: On the same assumption as Theorem 1, the mean delay of one-hop transmission is referred to as $\overline{D}(d)$. The minimum mean end-to-end delay $\overline{Dtot}_{min}$ is given by:

$$\overline{Dtot}_{min} = \overline{D}(d/n) \cdot n \tag{20}$$

if and only if $d_1 = d_2 = \ldots = d_n$.

Proof: Omitted because of the space limit. ∎

According to Theorem 1 and 2, we can conclude that for a pair of source and destination nodes and a given number of hops, the only scenario which minimizes both the mean energy and the mean delay is the one where the relaying clusters are equidistant along the linear path. Fig. 7 and Fig. 8 provide the comparison of the energy-latency trade-off between opportunistic communications and traditional P2P communications in Rayleigh block fading channel and AWGN

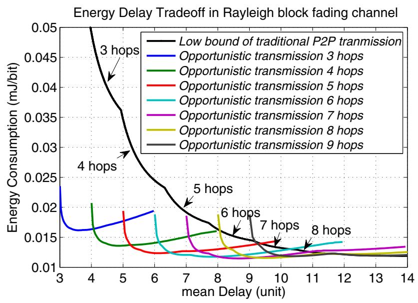

Fig. 7. Energy-latency trade-off with opportunistic communication and traditional P2P communication in Rayleigh block fading channel. $d = 900m$, $\alpha = 3$, *cf.* Table I for other related parameters.

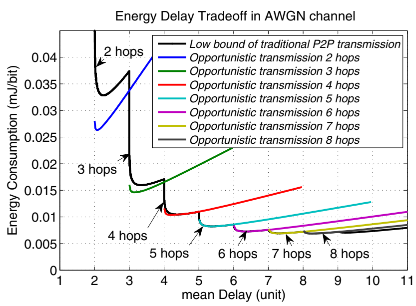

Fig. 8. Energy-latency trade-off with opportunistic communication and traditional P2P communication for AWGN channel. $d = 900m$, $\alpha = 3$, *cf.* Table I for other related parameters.

channel. The results on opportunistic communications and P2P communications are obtained using the branch and bound optimization and the approach in [13] respectively.

Fig. 7 shows that the energy efficiency is improved considerably under a delay limit smaller than 10 units. The lowest point of the curve of opportunistic communication corresponds to the optimal energy where the number of hops is 7, the mean delay is 8.8 units and the number of receivers is 2, which coincides with the results in Section III. While for P2P communications, the optimal energy point is obtained at 10 hops and the corresponding mean delay is 13.8 units. Note that the opportunistic routing needs less energy and latency than the P2P communication in Rayleigh block fading channel.

For AWGN channel, the energy efficiency benefits from the opportunistic routing under the constraint that the delay is smaller than 4 units as shown in Fig. 8. But the optimal energy point $(8.22units,\ 0.007mJ/bit)$ is obtained in a traditional P2P communication and the corresponding optimal number of hops is 8.

According to these results, it can be concluded that opportunistic communications are more energy efficient for Rayleigh block fading channels than for AWGN channels.

V. Conclusions

In this paper, we first integrate an unreliable link model into our energy model using a specific metric for energy efficiency: $\overline{EDRb}$. By optimizing $\overline{EDRb}$ for AWGN and Rayleigh block fading channels with and without delay constraint, we show that the channel state impacts the optimal number of receivers in a cluster. Meanwhile, the corresponding optimal transmission power and the optimal transmission range are derived. The energy-latency trade-off for one-hop and multi-hop transmissions are analyzed and compared with the trade-off given by traditional P2P communications. The main conclusion is that opportunistic communications exploiting spatial diversity are beneficial for Rayleigh block fading channels when a delay constraint is considered.

Acknowledgment

This work was partially funded by the French ANR project BANET, Body Area Networks and Technologies", supported by the Marie Curie OIF Action of the European Community's Sixth Framework Program (DistMO4WNet project) and supported by the project: Research on key techniques of wireless multimedia sensor networks (No.08220510900).

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