Exact and Heuristic Solutions for Energy-Aware Multihop Cooperation Over Wireless Networks

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***Abstract*—This paper addresses the problem of energy-aware multihop cooperation among the mobile terminals (MTs) that cooperatively download a common content from a wireless network. The base station (BS) unicasts or multicasts the content to selected MTs that, in turn, either unicast or multicast it to other MTs, forming a multihop ad hoc network with a predefined maximum allowed number of hops. This paper presents the optimization formulations whose solution gives the exact optimal set of receiving MTs from the BS, the optimal multihop ad hoc network, and the optimal unicasting and multicasting transmission bit rates that minimize the total energy consumption of the MTs. Second, a simplified multicasting formulation is proposed that has a close-to -optimal performance with notably lower computational complexity. Third, interference avoidance among the transmitting MTs is considered. For each presented formulation, the complexity is identified, and results show that some formulations can be efficiently solved for medium network sizes, while others are more computationally complex. Thus, polynomial-time heuristic solutions are presented that have close-to-optimal performance. Results demonstrate remarkable energy consumption reduction gains and wireless resources savings under various network scenarios.**

***Index Terms*—Cooperative communications, energy consumption, mobile-to-mobile cooperation, multihop, optimal content distribution, wireless multicasting.**

I. Introduction

One class of emerging mobile applications is simultaneous common-content distribution to a group of mobile terminals (MTs) over a broadband wireless network, such as news download (e.g., breaking news), multimedia multicasting (e.g., live sport events), or file distribution (e.g., device configuration files). This system model can represent classical wireless cellular networks in which the MTs are distributed within the cell range covered by a base station (BS), or it can represent a dense network where a large number of interested MTs are located within a small area such as a classroom, a café, an airport, or a mall. The addressed model is also of interest in emerging small-cell wireless networks in which it is expected that a large number of MTs will be interested to download a content of interest from a small cell served by a mini-BS or a femtocell access point [1].

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In a traditional scenario, the BS can unicast the content to each MT on a dedicated channel with a customized bit rate depending on its channel conditions; however, MTs usually face a throughput limitation problem while receiving on a long-range (LR) wireless technology due to the far distance of the MTs from the BS. Moreover, unicasting communication consumes a lot of cellular resources. For example, if K MTs are willing to receive the content, then K orthogonal resources are required when the MTs are in the vicinity of each other. On the other hand, multicasting is a key and promising solution for relieving the limited radio resources in wireless broadband networks, particularly when a group of MTs is interested in downloading the same content. However, multicasting schemes normally limit the transmission bit rate to the worst channel conditions among the requesting MTs so that all MTs can decode the content reliably, which increases the energy consumption of the MTs.

To overcome the throughput and power limitations of a given LR wireless technology, cooperative content distribution approaches have been proposed in the literature, by allowing the MTs to cooperate with each other over a short range (SR) wireless technology with higher data rates, due to the proximity of the MTs [2]–[16]. There are several ways for the content to be distributed from the BS to the MTs. For example, the BS can unicast [5]–[7], [10]–[13] or multicast the content [3], [4], [8], [9], [14]–[16] to selected MTs based on some predefined criteria; these MTs can then forward the received content to other MTs over mobile-to-mobile links. In the cooperative approaches, the MTs actively use two wireless interfaces: one interface to communicate with the BS over an LR wireless technology [such as Wireless Local Area Network (WLAN), Universal Mobile Telecommunications System (UMTS)/High Speed Packet Access, Worldwide Interoperability for Microwave Access (WiMAX), or Long-Term Evolution (LTE)] and another interface to communicate with other MTs using an SR wireless technology (such as Bluetooth or WLAN ad hoc mode).

Existing literature on cooperative common-content distribution over wireless networks aims at either reducing energy consumption at the MTs [4]–[7], [12], [13], increasing the network throughput [8]–[11], [15], [16], or decreasing the end-user communication costs [17], [18]. These works assume different cooperation models such as full cooperation in which all requesting MTs cooperate with each other [11], [13], [19], centralized location-based group formation performed by a central entity [4], [6], [8], [10], [12], [15], hybrid group formation performed by the MTs and the BS [7], [16], [17], or distributed group formation [5], [18]. In [2], we have presented a comprehensive survey on cooperative content distribution with mobile-to-mobile cooperation discussing the design alternatives and performance assessment methods. The major challenges for multihop cooperation over broadband wireless networks is to decide on the receiving MTs on LR and transmitting and receiving MTs on SR to optimize the metric of interest.

Most of the proposed works, in the literature, present a heuristic solution for the cooperative content distribution process, e.g., [5], [7], [10], [11], [15], [16], and [18]. For example, in [5], the MTs are grouped on SR according to the Bluetooth technology, where an MT will join a group/cluster if there is enough bandwidth between the group/cluster head and the receiving MT on the SR. Then, the cluster head downloads the content on an LR WLAN link and distributes it on SR links to the rest of MTs, within its group, using single-hop cooperation. The work in [11] assumes that the content is divided into several chunks and that all requesting MTs form one big cooperating group; every MT randomly pulls a chunk from the BS and sends it to the other MTs over SR links using single-hop cooperation on SR. In [7], each MT randomly selects and pulls a chunk through an LR cellular link and multicasts it, assuming single-hop cooperation, to all members in its cooperation group, which is formed using a heuristic algorithm.

The optimal multihop cooperation over broadband wireless networks is NP-hard for all unicast/multicast combinations on LR and SR as we will prove in Section III. Thus, it is unlikely to find an algorithm or optimization formulation whose optimal solution can be obtained in polynomial time. Some works investigated optimized solutions with major assumptions to reduce the complexity of the problem such as in [3], [4], [8], and [9]; these works assume multicasting from the BS and either unicasting or multicasting multihop cooperation among the MTs. In [3], Hua *et al.* optimized the number and set of video layers to be received by the MTs on LR; however, multihop cooperation on SR is determined using a heuristic algorithm that controls the number of hops by using a time-to-live field in the transmitted packets. In [4], it is assumed that the set of possible paths from the BS to the MTs is already predefined. Bhatia *et al.* in [8] did not formulate the optimization problem; however, they proposed an approximation algorithm, which is feasible in this case, since the considered system model is simplified in terms of grouping and bit rate selection on SR; it is assumed that the given area is divided into grids and that MTs within the same grid can only communicate using a four-hop ad hoc network heuristically formed using one transmission bit rate. Lo *et al.* in [9] assumed only unicasting communications on SR and did not impose any constraint on the number of hops; they modeled all possible multihop paths, which results in an exponential number of variables, and consequently, the optimal solution can be obtained only for very small network sizes.

Multihop transmission with too many hops will increase the latency of the communication. Thus, assuming that all links in the network have roughly the same transmission delay (which is a reasonable assumption in local area networks), then limiting the number of hops in the transmission to some small integer H helps in achieving fast and reliable communication protocols. Moreover, if each link has a certain probability of failure, guaranteeing that the content is delivered from the BS to the MTs within a certain probability also limits the number of hops.

None of the existing works investigated the optimal solution for multihop cooperation over broadband wireless networks that optimally determines the MTs that should receive on LR, the optimal multihop ad hoc network along with the optimal unicasting/multicasting transmission bit rates to minimize the total energy consumption of the MTs. Determining the optimal multicasting bit rate in the ad hoc network is challenging, and thus, the proposed multihop formulations, which assume multicasting on SR, require major assumptions. For example, the proposed framework in [3] assumes one transmission bit rate on SR, whereas the work in [4] captures unicasting communication on SR, and then, bit rate adaptation is performed to obtain the multicasting bit rate. Moreover, none of the formulations is generic, where the number of hops can be controlled.

A. Motivation

To this end, we have the following questions: Which is better between unicasting or multicasting on LR and SR in terms of energy consumption and required orthogonal resources? How shall the cooperative groups on SR be formed along with the optimal multicasting bit rate whenever multicasting communication is taking place on LR and SR? What is the complexity of finding the optimal solution of all these questions? The optimal solution to all these important questions have yet to be investigated due to several challenges. First, it is either shown or will be shown that the optimal multihop cooperation among the MTs over wireless networks is an NP-hard problem, even for single-hop cooperation on SR. Second, it is nontrivial to capture a tight mathematical formulation of the problem that can be efficiently solved for small to medium network sizes even if the problem is NP-hard. Third, it is not straightforward to identify the problem type and relate it to well-studied NP-hard problems, in the literature, which facilities the design of polynomial-time approximation and heuristic algorithms. Although the optimal solution is challenging to find, it is a necessity to understand the problem type and its complexity, identify the challenging design alternatives, and propose the suitable simplifications. Moreover, the optimal solution can serve as a benchmark upon which practical low-complexity heuristics can be developed and compared.

Usually, NP-hard problems are combinatorial in nature and, thus, are formulated using integer programming. Many years ago, integer programming formulations seemed impossible to solve; however, the last ten years have seen a remarkable advance in the ability to solve to near optimality difficult integer programming problems. This is due to a combination of 1) improved modeling, 2) superior linear programming software, 3) faster computers, 4) new cutting plane theory algorithms, and 5) branch-and-cut and integer programming decomposition algorithms [20].

Integer programming problems can be solved by any standard integer programming solving technique, e.g., linear programming (LP)-based branch-and-bound and cutting plane algorithms. Those are methods for global optimization in nonconvex problems, and they are guaranteed to converge to the optimal solution [20], [21]. In the worst case, the computational complexity of branch-and-bound methods exponentially grows with the number of integral variables; however, in some cases, the techniques converge with much less computations.

Currently, there are many solvers that can give provable optimal solutions or within 0.1%, 1%, or 5% from optimal in a reasonable amount of computer time [20]. There is, however, a cost where better models must be built. Thus, capturing a better problem formulation reduces the complexity of the problem that converges to the optimal solution in far fewer computations, compared with any other formulation [20], [21].

B. Contributions

In this paper, we tackle the problem of optimized energy-aware multihop cooperation over broadband wireless networks. The BS unicasts or multicasts the content to selected MTs over an LR wireless technology. Then, the MTs unicast or multicast the received content to other MTs using a multihop ad hoc network to minimize the total energy consumption of the MTs.

The central contributions of this work are summarized as follows. First, the optimization problems are formulated using mixed-integer LP (MILP) that captures the tightest possible formulation for all unicasting and multicasting combinations on LR/SR. Thus, the problem formulations are presented for unicasting/unicasting (i.e., unicasting on LR and unicasting on SR), unicasting/multicasting, multicasting/unicasting, and multicasting/multicasting communications along with the optimal unicasting or multicasting transmission bit rates on LR and SR. The proposed problem formulations control the maximum allowed number of hops H on SR. To our knowledge, we are the first to capture the controlled number of hops formulation in multihop cooperation initially presented in [22]. However, we are applying it, in this work, in the context of energy-aware multihop cooperation over broadband wireless networks. For example, setting $H = 1$ results in single-hop cooperation on SR, whereas setting $H = K - 1$, where K is the number of MTs, results in the minimum total energy consumption of the MTs. In this case, the optimal obtained number of hops can be lower than $K - 1$. Second, a simplified multicasting formulation is proposed that has a close-to-optimal performance with notably lower computational complexity. Third, we show that the proposed formulations can easily accommodate interference avoidance constraints among the transmitting MTs on the SR links. For each presented formulation, its complexity will be identified along with the pros and cons of each considered scheme. Results show that some formulations can be efficiently solved within a small computational time, whereas some other formulations prove to be more computationally complex. Thus, we present heuristic polynomial-time solutions with good performance compared with the optimal solution. All presented formulations are generic and can be applied to a wide range of network scenarios with different geographical topologies, channel models, and wireless technologies. A preliminary version of this work is presented in [6] and [23]. In [6], we only assume unicasting communication on LR and single-hop cooperation on SR; thus, the gains, challenges, and complexity of multihop cooperation and multicasting communication on LR have not been addressed. In [23], we present a preliminary model for the multicasting/multicasting communication case without discussing its complexity. Moreover, in this work, a more comprehensive and realistic energy consumption model is considered, in which the energy consumed per second is a function of the transmission bit rate; this required further adaptations on the problem formulation presented in [23]. The other three communication schemes were neither presented nor analyzed and compared among each other in terms of complexity and performance. In addition, suitable polynomial-time heuristic solutions have yet to be proposed.

This paper is organized as follows. Section II presents the system model, main parameters, and energy consumption formulations. Section III presents the optimization problems' formulations for the various LR/SR transmission schemes. Interference avoidance among the transmitting MTs is introduced in Section IV. Polynomial-time heuristic solutions are presented in Section V. Results and analysis are discussed in Section VI. Finally, conclusions are drawn in Section VII.

II. System Model

There are no standardized content distribution protocols that enable the MTs to intelligently connect to a cellular network and among each other to download the content cooperatively. All the accomplished works assume either generic system models or specific LR (e.g., UMTS and LTE) and SR (e.g., Bluetooth and WLAN) technologies with no standardized cooperation between them.

For practical implementations, intelligent protocols need to be developed that should be aware of whether to minimize the cost, reduce the required cellular resources, minimize the energy consumption of the MTs, etc. To achieve these performance gains, several implementation challenges need to be overcome, and more studies need to be accomplished. Our contribution, in this direction, is to investigate the optimal LR/SR distribution strategies so as to minimize the total energy consumption of the MTs. To achieve this goal, we choose a generic system model in which the LR and SR links are technology independent. Using a generic system model provides answers to important fundamental questions related to the optimization problem type and complexity, optimized bounds on network performance, tradeoffs and interplay between various design alternatives, etc., that the network designers can make use of, in the future, in the design of standardized cooperative content distribution protocols.

Consider K requesting MTs interested in downloading a common content of size S_{T} bits in the range of a BS, and let $\mathcal{K}$ denote the set of MTs. The BS is connected via a wired local area network to the server that holds the content. The BS transmits the content to selected MTs with good channel conditions on LR, which, in turn, transmit it to other MTs on SR links (see Fig. 1). We denote the set of MTs that directly receive from the BS as $\mathcal{L}$.

The BS plays a significant role in determining the energy consumption of the MTs that should receive on LR. Since the BS is connected to a power line, minimizing its energy consumption is not of concern. As a result, it can use its available power with an adaptive transmission bit rate. For example, if the MTs forward the content using single-hop

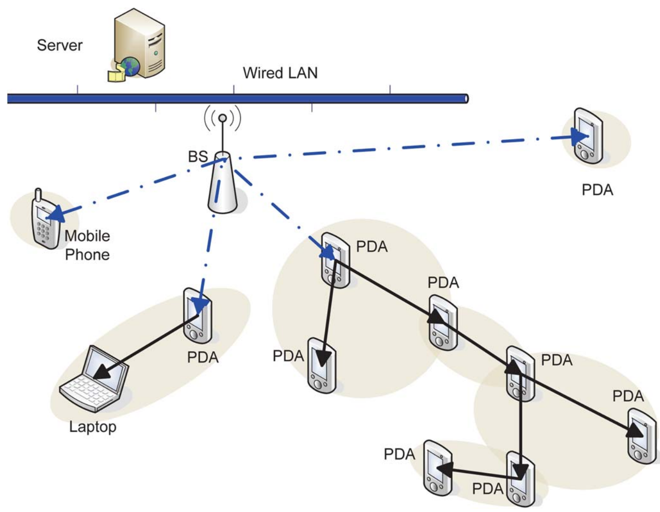


Fig. 1. System model.

transmission on SR, then the BS will decrease its transmission bit rate to transmit the content to the far MTs with bad channel conditions on LR. Those MTs can then help other far MTs with high data rates on SR, which decreases the overall energy consumption. Even with multihop cooperation, the BS can find itself forced to decrease its transmission bit rate to serve the far MTs that do not have neighboring MTs to cooperate with. This can happen with nonuniformly distributed MTs; for instance, a group of MTs can be found in a close geographical area, whereas other interested MTs might be far from that group as shown in Fig. 1. In this case, the close MTs can benefit from multihop cooperation on SR, whereas the dispersed MTs cannot be served except by the BS. This work proposes optimization formulations that can accommodate any MT distribution.

We assume static scenarios for the problem formulations and solutions, whereas the impact of mobility is studied and analyzed in Section VI-D, taking into account practical considerations.

TABLE I
MAIN PARAMETERS AND VARIABLES

Parameters	
$\mathcal{K}$	the set of requesting MTs, where a MT is referred to as MT k, $k = 1, \ldots, K$
$\mathcal{K}'$	the set that contains the BS with index $k' = 0$ and the K requesting MTs with indexes $k' = k = 1, \ldots, K$
S_{T}	the size of the common content in bits
$d_{k'j}$	distance between transmitter (BS/MT) k' and MT j
$h_{k'j}$	channel fading between transmitter (BS/MT) k' and MT j
$R_{\mathrm{L},k}$	transmission bit rate on LR from the BS to MT k
$R_{\mathrm{S},kj}$	transmission bit rate on SR from MT k to MT j
R_{S}	fixed transmission bit rate that all MTs transmit with on SR (only used in Section III.C)
$P_{\mathrm{t},k'j}$	transmit power of transmitter (BS/MT) k' to MT j
P_t	maximum transmit power capability of a MT
$P_{\mathrm{r},k'j}$	received power at MT j from transmitter (BS/MT) k'
$\gamma_{k'j}$	received signal-to-noise ratio at MT j from transmitter (BS/MT) k'
$M_{k'j}$	order of M-QAM modulation received at MT j from transmitter (BS/MT) k'
$E_{\mathrm{Rx,L}}(R_{\mathrm{L},k})$	energy consumed per second by MT k while receiving data on LR with bit rate $R_{\mathrm{L},k}$
$E_{\mathrm{Rx,S}}(R_{\mathrm{S},kj})$	energy consumed per second by MT j while receiving data on SR from MT k with bit rate $R_{\mathrm{S},kj}$
$E_{\mathrm{Tx}}(R_{\mathrm{S},kj})$	energy consumed per second by MT k while transmitting data on SR to MT j with bit rate $R_{\mathrm{S},kj}$
Variables	
y_k	a binary variable that indicates whether MT k receives data on LR, i.e., $y_k = 1$ when MT k receives on LR, and $y_k = 0$ otherwise
v_{kj}^h	a binary variable that indicates whether MT k sends data to MT j on SR on hop h, i.e., $v_{kj}^h = 1$ when MT k sends to MT j on hop h, and $v_{kj}^h = 0$ otherwise
z_k	a positive variable that determines the bit rate that MT k transmits with to the other MTs within its group
c_{kj}	a positive variable that determines the bit rate that MT j receives with from MT k
T_k	a positive variable that determines the energy per bit consumed by MT k to receive on LR
Z_k	a positive variable that determines the energy per bit consumed by MT k to transmit to the other MTs within its group
Z_k'	a positive variable that determines the energy per bit consumed by the MTs receiving from MT k within its group
C_{kj}	a positive variable that determines the energy per bit consumed by MT j to receive from MT k

A. Parameters and Variables

We present the main parameters and variables that affect the energy consumption formulation in the considered cooperative content distribution framework in Table I.

1) Bit Rate Calculation: The channels on the LR and SR links are assumed to be orthogonal. The received power at MT j, i.e., $P_{r,k'j}$, can be linked to the transmitted power of transmitter k', i.e., $P_{t,k'j}$, by a channel gain $G_{k'j}$, and the relation can be expressed as follows [24]:

$$(G_{k'j})_{\mathrm{dB}} = \left(\frac{P_{r,k'j}}{P_{t,k'j}}\right)_{\mathrm{dB}} = 10\log_{10}\kappa\left(\frac{d_{k'j}}{d_0}\right)^{-\nu} - (h_{k'j})_{\mathrm{dB}} \quad (1)$$

where κ is a path-loss constant that depends on the antenna characteristics and the wireless environment, ν is the path-loss exponent, d_0 is a reference distance (typically 1 or 10 m in indoor or SR outdoor scenarios), $d_{k'j}$ is the distance between the transmitter and the receiver, and $h_{k'j}$ is a random variable representing channel fading.

Given the orthogonality of the channels, the signal-to-noise ratio (SNR) of each MT is given by $\gamma_{k'j} = P_{r,k'j}/\sigma^2$, where $P_{r,k'j}$ is the received power given by (1), and σ^2 is the thermal noise power. We assume rate adaptation based on M-ary quadrature amplitude modulation (M-QAM); therefore, given the passband bandwidth $W_{k'j}$ of the channel, the bit rates on the LR or SR channels are given by $R_{k'j} = \log_2(1 + \delta\gamma_{k'j}) \cdot W_{k'j}$, where $\delta = -1.5/\ln(5P_e)$ is the SNR gap for M-QAM [24]. To simplify the notations of the LR and SR bit rates, we set $R_{\mathrm{L},k} = R_{0k}$ and $(R_{\mathrm{S},kj} = R_{kj}, k \geq 1)$.

2) Energy Consumption Modeling: There are several energy consumption models, in the literature, that have been validated through testbed implementations.

First, it is conventional in the literature (e.g., [25]) that the energy consumed per unit time during transmission is given as follows: $E_{\mathrm{Tx}} = (P_t/\eta(P_t)) + E_{\mathrm{ct}}$, where P_t is the power of the transmitted signal, $\eta(P_t)$ is the power conversion efficiency of the power amplifier, and E_{ct} is the circuitry power (energy per unit time) consumed during transmission. However, the energy consumed during reception is due to the receive circuity of the MT. To avoid confusion of the transmit and receive power of the radiated signal, i.e., P_t and P_r, respectively, with the power consumed within the circuity of the MT during transmission and reception, i.e., E_{Tx} and E_{Rx}, respectively, we will refer to the latter power as the energy consumed per unit time by the MT.

The energy consumed per unit time by an MT during transmission and reception can be considered constant at a fixed transmission bit rate [7], [19] or for various transmission bit rates between the communicating entities using adaptive rate control [26]. In [26], Mahmud *et al.* set up an experimental testbed to measure the energy consumption of the MT on several wireless interfaces adopting different technologies. They clearly show that the energy consumption within an MT can be modeled as a constant energy per unit time multiplied by the total time for which a wireless interface is active; this time depends on the channel rate that can take different values, based on adaptive rate control. Whereas, some other works assume that the energy consumed per unit time depends on the transmission bit rate, i.e., $E(R)$, as shown in [27] and [28]. In this case, the energy consumed per unit time is related to the transmission bit rate using a lookup table for the various transmission bit rates [27], [28]. It is evident in both works [27], [28] that as the transmission bit rate R increases, the energy per bit $E(R)/R$ decreases, which favors the use of the highest transmission bit rate between any two communicating entities achieved when the MT is transmitting with its highest transmission power capability P_t.

In this paper, we formulate general expressions that can be applied using any of the aforementioned methods for the energy consumption calculation. Thus, we formulate the problems assuming that the consumed energies per unit time, i.e., $E(R)$, are a function of the bit rate, i.e., R (bits/unit time). In this case, there should be a lookup table, obtained through testbed measurements, that associates for each bit rate the corresponding energy consumption during reception and transmission on LR and SR. Note that we assume that all MTs transmit with maximum power $P_t (P_{t,kj} = P_t, k \geq 1)$ with rate adaptation depending on the received SNRs, which determine the maximum achieved transmission bit rates between the communicating entities. The achieved bit rate, i.e., R, determines accordingly the required energy consumption per unit time $E(R)$ using a lookup table. This strategy minimizes the required energy per bit $E(R)/R$, since $E(R)/R$ decreases as R increases, as shown in [27] and [28], which minimizes the overall energy consumption of the MTs. Power consumption at the BS is ignored, since BSs normally rely on power line cables instead of batteries and, thus, do not have energy consumption constraints. In this case, we also assume that the BS is transmitting to all MTs with the same power $P_{t,0k}$ with rate adaptation depending on the received SNRs.

B. Energy Consumption Formulation

Here, the energy consumption expressions for the unicasting/unicasting and the multicasting/multicasting problems will be derived. The other two LR/SR communication strategies, which are unicasting/multicasting and multicasting/unicasting, can then be easily deduced.

1) Energy Consumption Formulation for Unicasting/Unicasting: Energy consumption can be modeled as a linear function that is proportional to the number of bits sent and received or as a function of the time duration while transmitting and receiving [7], [19], [26]. In the sequel, the energy consumed is calculated as the product between the energy consumed per second while transmitting/receiving and the transmission/reception time duration in seconds. The energy $E_{L,k}$ consumed by MT k for receiving the content on LR is

$$E_{\mathrm{L},k} = y_k \cdot S_{\mathrm{T}} \frac{E_{\mathrm{Rx,L}}(R_{\mathrm{L},k})}{R_{\mathrm{L},k}} \tag{2}$$

where the decision variable $y_k = 1$, if MT k receives on LR and $y_k = 0$ otherwise. The value of $S_{\mathrm{T}}/R_{\mathrm{L},k}$ represents the required time to send the content to MT k on the LR link.

Upon receiving the content, MT k will send the content to MT j on hop h on SR, if $v_{kj}^h = 1$; otherwise, $v_{kj}^h = 0$. Thus, $\sum_{h=1}^{H} v_{kj}^h$ is a binary variable since MT k might transmit the content to MT j, only once, on one of the H hops. MT k consumes an additional energy to send the content to each MT j within its group with a bit rate $R_{\mathrm{S},kj}$ that is adapted according to the channel conditions between the communicating MTs. The associated energy consumption for MT k to transmit to MT j on one of the H hops is given by

$$E_{\mathrm{S,Tx},kj} = \sum_{h=1}^{H} v_{kj}^h \cdot S_{\mathrm{T}} \frac{E_{\mathrm{Tx,S}}(R_{\mathrm{S},kj})}{R_{\mathrm{S},kj}}. \tag{3}$$

Following a similar approach for computing the energy consumed by MT k while receiving the content on SR from MT j on one of the H hops, we get

$$E_{\mathrm{S,Rx},jk} = \sum_{h=1}^{H} v_{jk}^h \cdot S_{\mathrm{T}} \frac{E_{\mathrm{Rx,S}}(R_{\mathrm{S},jk})}{R_{\mathrm{S},jk}}. \tag{4}$$

By using (2)–(4), the total energy consumed by the K MTs can be expressed as follows:

$$\begin{aligned} E_{\mathrm{T,U}} &= S_{\mathrm{T}} \sum_{k=1}^{K} y_k \frac{E_{\mathrm{Rx,L}}(R_{\mathrm{L},k})}{R_{\mathrm{L},k}} \\ &+ S_{\mathrm{T}} \sum_{h=1}^{H} \sum_{k=1}^{K} \sum_{j=1, j\neq k}^{K} v_{kj}^h \frac{E_{\mathrm{Tx,S}}(R_{\mathrm{S},kj}) + E_{\mathrm{Rx,S}}(R_{\mathrm{S},kj})}{R_{\mathrm{S},kj}}. \end{aligned} \tag{5}$$

2) Energy Consumption Formulation for Multicasting/Multicasting: For multicasting communication, all transmitting entities (BS/MT) transmit only once with the lowest bit rate among the receiving MTs so that all of them can decode the content reliably.

For multicasting on LR, the energy consumed by MT $k \in \mathcal{L}$ for receiving over LR depends on the bit rate that the MTs receive with on LR. The multicasting bit rate, i.e., x, on LR should be equal to the minimum bit rate among the receiving

MTs on LR, i.e., $x = \min_{k\in\mathcal{L}} R_{\mathrm{L},k}$. Thus, the energy consumed by MT k receiving over the LR is

$$E_{L,k} = y_k \cdot S_{\mathrm{T}} \frac{E_{\mathrm{Rx,L}}(x)}{x}. \tag{6}$$

For multicasting on SR, the energy consumed by MT k to transmit to the other MTs within its group G depends on the minimum bit rate, i.e., z_k, of the receiving MTs within its group on SR, i.e., $z_k = \min_{j\in G} R_{\mathrm{S},kj}$. Thus, the energy consumed by MT k to transmit on SR is

$$E_{S,Tx,k} = u_k \cdot S_{\mathrm{T}} \frac{E_{\mathrm{Tx,S}}(z_k)}{z_k}. \tag{7}$$

Note that when $u_k = 1$, this indicates that MT k is transmitting on SR; however, it does not specify to which MT it is transmitting. The variable v_{kj}^h precisely indicates on which hop MT k is transmitting and to which MTs. Thus, there is a clear relation between u_k and v_{kj}^h, and it can be stated as follows: $u_k \geq \sum_{h=1}^{H} v_{kj}^h \forall j$.

The energy consumed by MT j to receive from MT k on SR is

$$E_{S,Rx,kj} = \sum_{h=1}^{H} v_{kj}^h \cdot S_{\mathrm{T}} \frac{E_{\mathrm{Rx,S}}(c_{kj})}{c_{kj}} \tag{8}$$

where c_{kj} should be equal to z_k since MT j that receives from MT k should receive with the transmission bit rate of MT k; this condition will be modeled in the constraints of the optimization formulation of the problem.

Thus, the total energy consumed in the network is

$$E_T = S_{\mathrm{T}} \sum_{k=1}^{K} y_k \frac{E_{\mathrm{Rx,L}}(x)}{x} + S_{\mathrm{T}} \sum_{k=1}^{K} u_k \frac{E_{\mathrm{Tx,S}}(z_k)}{z_k} + S_{\mathrm{T}} \sum_{h=1}^{H}\sum_{k=1}^{K}\sum_{j=1,j\neq k}^{K} v_{kj}^h \frac{E_{\mathrm{Rx,S}}(c_{kj})}{c_{kj}}. \tag{9}$$

The total energy consumed by the K requesting MTs, in the noncooperative case, is given by (10) and (11) when the BS multicasts and unicasts the content, respectively, to all the MTs on LR, i.e.,

$$E_{\mathrm{Nocoop_M}} = K \cdot S_{\mathrm{T}} \cdot \frac{E_{\mathrm{Rx,L}}(\min_{k\in\mathcal{K}} R_{\mathrm{L},k})}{\min_{k\in\mathcal{K}} R_{\mathrm{L},k}} \tag{10}$$

$$E_{\mathrm{Nocoop_U}} = \sum_{k=1}^{K} S_{\mathrm{T}} \cdot \frac{E_{\mathrm{Rx,L}}(R_{\mathrm{L},k})}{R_{\mathrm{L},k}}. \tag{11}$$

III. Optimization Problem Formulation

This section presents the optimization problem formulations for optimal unicasting/unicasting and optimal multicasting/multicasting. A simplified multicasting/multicasting problem formulation is proposed, which proves to be notably less computationally complex than the optimal multicasting/multicasting problem. The optimization formulations for the other two LR/SR communication strategies, which are unicasting/multicasting and multicasting/unicasting, can then be easily deduced. Unicasting communication has different properties than multicasting communication in terms of the number of transmissions, the transmission energy, and the used bit rates, which necessitates different problem formulations.

To compute the solution of the formulated optimization problems, a central entity should collect the needed network information, which are the achieved bit rates on LR and SR, i.e., $R_{\mathrm{L},k}$ and $R_{\mathrm{S},kj}$, respectively. In practical scenarios, each MT can estimate the channel conditions with respect to its neighboring MTs and feed back this information to the BS. To estimate the channel gain (and subsequently the bit rate), one can adopt classical signal processing techniques such as those in [29]. For example, an MT can send a pilot signal that its neighboring MTs can only hear, then those MTs can estimate the channel and feed it back to the BS. Thus, even if the solution is centralized; however, given that the transmission range of an MT is limited, an MT collects the information about its neighboring MTs only and not all MTs in the network. When the BS collects the needed network information, it will compute the centralized solution. Based on the obtained solution, the BS will send the content to each MT k whose $y_k = 1$. The content can, for example, be sent in frames that contain the MAC address of the MT that should receive it. The BS should also send to each MT k the list of the MAC addresses of MTs j that they should forward the content to for all $v_{kj}^h = 1$. In relatively static environments, the MT can directly initiate the transmission with the MTs that it received their MAC addresses from the BS since the estimated bit rate would still be the same. In highly mobile environments, the MT can resend pilot signals to the MTs with the intended MAC addresses to reestimate the updated bit rate based on mobility, and then, the transmission process can start. This practical LR/SR content distribution procedure, after computing the solution at the BS, is applicable to all the proposed optimal and heuristic approaches.

A. *Optimal Unicasting/Unicasting Problem Formulation*

The optimal unicasting/unicasting problem formulation, in which the maximum allowed number of SR hops can be controlled, will be presented. For each value of H, a different solution is expected. The optimization formulation can be expressed as follows:

$$\min_{\mathbf{y},\mathbf{v}} S_{\mathrm{T}} \sum_{k=1}^{K} y_k f_k + S_{\mathrm{T}} \sum_{h=1}^{H}\sum_{k=1}^{K}\sum_{j=1,j\neq k}^{K} v_{kj}^h s_{kj} \tag{12}$$

subject to

$$v_{kj}^1 \leq y_k \ \forall k\, \forall j \tag{13}$$

$$v_{ji}^{h+1} \leq \sum_{k=1}^{K} v_{kj}^h \ \forall j\, \forall i\, \forall h \tag{14}$$

$$\sum_{k=1}^{K}\sum_{h=1}^{H} v_{kj}^h + y_j = 1 \ \forall j \tag{15}$$

$$y_k \in \{0,1\} \forall k, v_{kj}^h \in \{0,1\} \forall k\, \forall j\, \forall h \tag{16}$$

where $f_k = E_{\mathrm{Rx,L}}(R_{\mathrm{L},k})/R_{\mathrm{L},k}$, and $s_{kj} = (E_{\mathrm{Tx,S}}(R_{\mathrm{S},kj}) + E_{\mathrm{Rx,S}}(R_{\mathrm{S},kj}))/R_{\mathrm{S},kj}$; the indexes k, j, and i vary between 1 and K, and h varies between 1 and H. This problem is a binary LP problem. The first constraint (13) guarantees that MT k can transmit to MT j on the first hop on SR, i.e., $v_{kj}^1 = 1$, only if MT k receives data on LR, i.e., when $y_k = 1$. The second constraint (14) allows MT j to transmit to MT i on hop $h+1$, only if MT j receives from any MT k on hop h. Note that $\sum_{k=1}^{K} v_{kj}^h \leq 1$ since every MT j receives the content only once. The third constraint (15) guarantees that every MT j receives the content either on LR, when $y_j = 1$, or on SR on one of the hops, if $\forall j$, one of the v_{kj}^h variables is 1. The last constraint (16) sets the variables to be binary.

1) Problem Hardness:

Theorem 1: The optimal energy-aware unicasting/unicasting problem with multihop cooperation on SR in which the number of hops H is controlled is NP-complete.

Proof: The optimal unicasting/unicasting problem in which the number of hops on SR is limited to H is similar to the k-hop minimum spanning tree problem (kHMST), where $k = H + 1$ represents the number of hops from the BS. The connection cost between the nodes of the tree is the energies consumed to transmit and receive, as shown in Fig. 2(a). Let $G(\mathcal{K}', A)$ represent the graph that connects the BS and MTs among each other; $\mathcal{K}'$ is the set that contains the BS with index $k' = 0$ and the K requesting MTs with indexes $k' = k = 1, \ldots, K$, and A is the adjacency matrix that contains the energy consumption costs between the communicating entities. The objective is to find the spanning tree that connects all nodes of $\mathcal{K}'$ to guarantee that all MTs receive the content such that the connection cost (energy consumption) is minimized and the maximum tree depth does not exceed $H + 1$.

The kHMST is NP-complete. To prove this fact, consider the case where the maximum allowed number of hops H on SR is 1. This problem is similar to the complete uncapacitated facility location (CUFL) problem, which is NP-hard [30]. The CUFL problem is defined as follows: Given a set $\mathcal{F}$ of potential facility locations, a subset $\mathcal{F}' \subseteq \mathcal{F}$ should be opened to serve a set $\mathcal{D}$ of demand points. The cost of opening a facility $k \in \mathcal{F}$ is f_k, and the connection cost of demand point $j \in D$ with facility k is s_{kj}. The objective is to find a subset $\mathcal{F}' \subseteq \mathcal{F}$ that should be opened to serve all demand points in $\mathcal{D}$ while minimizing the total cost. For the CUFL problem [30], every location is a demand point and can be a potential facility as in our case. Consequently, the optimal unicasting/unicasting problem assuming single-hop cooperation on SR is NP-hard.

Thus, the more general optimal unicasting/unicasting problem where the number of hops $H > 1$ is NP-hard. It is straightforward to show that a solution for the optimal unicasting/unicasting problem assuming multihop cooperation on SR can be verified in polynomial time; thus, the problem is NP-complete. ■

Theorem 2: The optimal energy-aware unicasting/unicasting problem with multihop cooperation on SR in which the number of hops H is not controlled can be modeled as a minimum spanning tree (MST) problem that can be obtained in polynomial time.

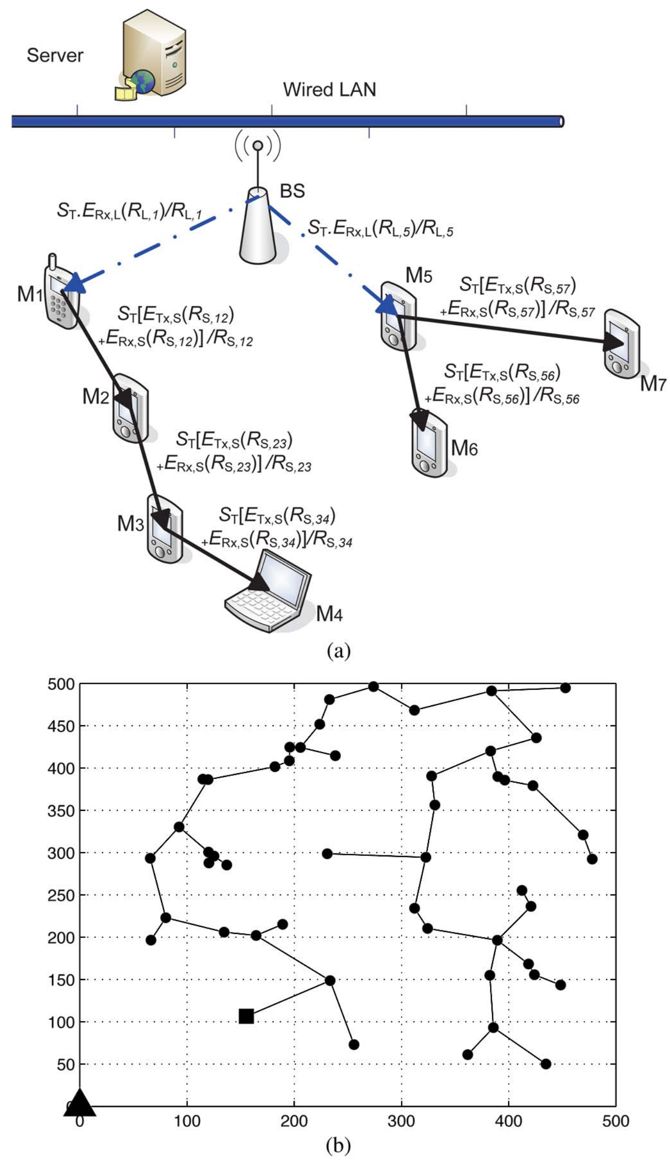


Fig. 2. Minimum energy spanning tree (MEST). The triangle represents the BS. The square represents an MT that receives on LR. The circle represents an MT that transmits and/or receives on SR; the link between sending and receiving MTs is marked by a solid line. (a) Connection costs in MEST. (b) MEST for 50 MTs showing that 28 hops are required.

Proof: If there is no limit on the number of hops, then the unicasting/unicasting tree can be of any depth, which is, at most, K. The objective, in this case, is just to minimize the connection costs (energy consumption) of the MTs. This problem turns to be exactly an MST problem whose connection costs are the energy consumption values between the communicating entities. Thus, the optimal unicasting/unicasting problem with multihop cooperation on SR in which the number of hops H is not controlled can be modeled as an MST, which can be solved to optimality in polynomial time using Prim's algorithm [31]. ■

However, a major drawback of the increased number of hops is the obtained delay and link failure probability in the network particularly with the mobility of the MTs. For example, Fig. 2(b) shows the optimal unicasting/unicasting tree, for a set of $K = 50$ MTs, that minimizes the overall MTs' energy consumption obtained using Prim's algorithm. It is clear that the optimal number of hops H reaches up to 28 hops on SR for the content to be delivered from the BS to all MTs through multihop relaying. There can be also scenarios where the number of hops can reach $K-1$ on SR. Thus, controlling the number of hops is a better design alternative; however, it turns the problem to be NP-complete that can only be efficiently solved for small to medium network sizes.

B. Optimal Multicasting/Multicasting Problem Formulation

This section presents the optimal formulation for joint content distribution and group formation for multicasting on LR and SR links to minimize the total energy consumption of the MTs presented in (9). It can be easily seen that the objective presented in (9) is not linear, which turns the problem to be a mixed-integer nonlinear programming (MINLP) problem. MINLP problems are precisely so difficult to solve, because they combine all the difficulties of both of their subclasses: the combinatorial nature of mixed-integer programs (MIPs) and the difficulty of solving nonconvex nonlinear programs (NLP). Because subclasses MIP and NLP are among the class of theoretically difficult problems (NP-complete), it is not surprising that solving MINLP can be a challenging and daring venture [32].

In this paper, we will show how to linearize the objective by using a sophisticated formulation that gives exactly the same optimal solution as the nonlinear formulation. This can be done by following the next steps. First, we do the following change of variables $T_k = E_{\mathrm{Rx,L}}(x)/x$, $Z_k = E_{\mathrm{Tx,S}}(z_k)/z_k$, and $C_{kj} = E_{\mathrm{Rx,S}}(c_{kj})/c_{kj}$. Thus, the new objective becomes

$$E_T = S_{\mathrm{T}}\left[\sum_{k=1}^{K} y_k \cdot T_k + \sum_{k=1}^{K} u_k \cdot Z_k + \sum_{h=1}^{H}\sum_{k=1}^{K}\sum_{j=1,j\neq k}^{K} v_{kj}^h \cdot C_{kj}\right]. \tag{17}$$

The objective is still not linear; however, it can be linearized since y_k, u_k, and $\sum_{h=1}^{H} v_{kj}^h$ are binary variables and satisfy the following conditions: $T_k > 0$ only if $y_k = 1$; otherwise, both are zeros; $Z_k > 0$ only if $u_k = 1$; otherwise, both are zeros; and $C_{kj} > 0$ only if $\sum_{h=1}^{H} v_{kj}^h = 1$; otherwise, both are zeros. Note that there is also a direct relation between u_k and v_{kj}^h, where $u_k \geq \sum_{h=1}^{H} v_{kj} \forall j$. By adding the necessary constraints, the problem can be formulated as

$$\min_{\mathbf{y},\mathbf{v},\mathbf{q},\mathbf{T},\mathbf{Z},\mathbf{Z}',\mathbf{C}} \sum_{k=1}^{K} S_{\mathrm{T}}\left[T_k + Z_k + \sum_{j=1,j\neq k}^{K} C_{kj}\right] \tag{18}$$

subject to

$$v_{kj}^1 \leq y_k \ \forall k \ \forall j \tag{19}$$

$$v_{ji}^{h+1} \leq \sum_{k=1}^{K} v_{kj}^h \ \forall j \ \forall i \ \forall h \tag{20}$$

$$\sum_{k=1}^{K}\sum_{h=1}^{H} v_{kj}^h + y_j = 1 \ \forall j \tag{21}$$

$$q \geq y_k \frac{E_{\mathrm{Rx,L}}(R_{L,k})}{R_{L,k}} \ \forall k \tag{22}$$

$$T_k \geq q - \max_k \left(\frac{E_{\mathrm{Rx,L}}(R_{\mathrm{L},k})}{R_{\mathrm{L},k}}\right)(1-y_k) \ \forall k \tag{23}$$

$$Z_k \geq \frac{E_{\mathrm{Tx,S}}(R_{\mathrm{S},kj})}{R_{S,kj}} \sum_{h=1}^{H} v_{kj}^h \ \forall k \ \forall j \tag{24}$$

$$Z'_k \geq \frac{E_{\mathrm{Rx,S}}(R_{\mathrm{S},kj})}{R_{S,kj}} \sum_{h=1}^{H} v_{kj}^h \ \forall k \ \forall j \tag{25}$$

$$C_{kj} \geq Z'_k - \max_j \left(\frac{E_{\mathrm{Rx,S}}(R_{\mathrm{S},kj})}{R_{\mathrm{S},kj}}\right)\left(1 - \sum_{h=1}^{H} v_{kj}^h\right) \ \forall k \ \forall j \tag{26}$$

$$y_k \in \{0,1\}\forall k, v_{kj}^h \in \{0,1\}\forall k \ \forall j \ \forall h \tag{27}$$

$$q \geq 0, \{T_k \geq 0, Z_k \geq 0, Z'_k \geq 0\} \ \forall k, \ C_{kj} \geq 0 \forall k \ \forall j. \tag{28}$$

The first three constraints are explained in detail in Section III-A. The fourth constraint (22) determines the maximum receive energy per bit, i.e., q, which corresponds to the minimum bit rate between the BS and receiving MTs k on LR since $E(R)/R$ is a decreasing function as explained in Section II-A.2. For example, if $q \geq 0.1, q \geq 0.2$ and $q \geq 0.3$, then the minimum value of q that satisfies all constraints is $q = 0.3$. The fifth constraint (23) determines the energy per bit consumed by MT k to receive on LR. Note that all MTs receiving from the BS consume the same amount of energy per bit since they receive with the same multicasting bit rate. This constraint is the same as $T_k \geq y_k \cdot q$; however, to linearize it, we write it as shown in (23). If an MT receives on LR, i.e., when $y_k = 1$, then $T_k = q$. If MT k does not receive on LR, then T_k is always greater than a negative value since we are subtracting q from the highest energy per bit coefficient that MT k can achieve, but since $T_k \geq 0$, as shown in (28), the minimization problem sets $T_k = 0$. The sixth constraint (24) determines the maximum energy per bit, i.e., Z_k, consumed by MT k to transmit on SR; it corresponds to the minimum bit rate between the transmitting MT k and receiving MTs j in every group. If MT k is not sending to any MT j on the SR links, i.e., when $\sum_{h=1}^{H} v_{kj}^h = 0 \forall j$, then $Z_k = 0$. The seventh constraint (25) determines the maximum energy per bit consumed by the MTs receiving from MT k within its group (i.e., when $\sum_{h=1}^{H} v_{kj}^h = 1$), which should also correspond to the same minimum bit rate obtained in (24) since both constraints have the same decision variable v_{kj}^h. The eighth constraint (26) determines the energy per bit consumed by MT j to receive from MT k. Note that all MTs receiving with the same bit rate consume the same energy per bit during reception. This constraint should be written as $C_{kj} \geq Z'_k \cdot \sum_{h=1}^{H} v_{kj}^h$. However, to linearize this constraint, we have written it as shown in (26). If MT j receives from MT k on hop h, i.e., $v_{kj}^h = 1$, then $C_{kj} = Z'_k$, and if $\sum_{h=1}^{H} v_{kj}^h = 0$, then C_{kj} is greater than a negative value since we are subtracting Z'_k from the highest energy per bit coefficient that MT k can achieve, but since $C_{kj} \geq 0$, the optimization problem sets $C_{kj} = 0$. The last constraints (27) and (28) determine the types of the variables; y_k and v_{kj}^h are binary variables, whereas the rest of the variables are real positive.

C. Simplified Multicasting/Multicasting Problem Formulation

The search space for finding the optimal grouping and multicasting bit rates on LR and SR grows exponentially fast as K increases. Thus, more constraints can be added to reduce the size of the search space. The number of variables and constraints is on the order of K to find the optimal bit rate on LR, whereas it is on the order of HK^2 to find the optimal grouping and the bit rate within each group on SR.

To reduce the problem's complexity, we will relax the constraint of finding the optimal bit rate on SR within each group. We will set the SR bit rate to a predefined threshold value R_{S}, which corresponds to a transmit and receive time per bit $T_S = 1/R_{\mathrm{S}}$ (T_S and R_{S} are parameters in this case and not variables). In this case, only MT j that has an SR bit rate $R_{S,kj}$ higher than or equal to R_{S} will be a candidate for receiving from MT k so that it can decode the content reliably. Setting a target multicasting bit rate can be mapped to setting a maximum transmission range for each MT. If two MTs are separated by more than the maximum transmission range, they cannot cooperate.

We chose to relax this constraint since it is logical to set a maximum transmission range for the MTs. Moreover, the MTs will cooperate if they are within a close distance of each other; otherwise, the BS will serve distant MTs since its transmission power capability is much higher. In addition, assuming that all transmitting MTs transmit with the same bit rate results in a relatively fair solution. In this case, it is guaranteed that none of the MTs is reducing its transmission bit rate to reach relatively far MTs that increase its energy consumption.

The simplified multicasting problem becomes

$$\min_{\mathbf{y},\mathbf{v},\mathbf{u},\mathbf{q},\mathbf{T}} \sum_{k=1}^{K} S_{\mathrm{T}} \left[T_k + \frac{E_{\mathrm{Tx,S}}(R_{\mathrm{S}})}{R_{\mathrm{S}}} u_k + \frac{E_{\mathrm{Rx,S}}(R_{\mathrm{S}})}{R_{\mathrm{S}}} \sum_{h=1}^{H} \sum_{j=1, j\neq k}^{K} v_{kj}^h \right] \quad (29)$$

subject to

(19)–(23)

$$\sum_{h=1}^{H} v_{kj}^h \leq u_k \; \forall k \; \forall j \quad (30)$$

$$v_{kj}^h = 0, \text{ if } (R_{S,kj} < R_{\mathrm{S}}) \forall k \; \forall j \; \forall h \quad (31)$$

$$\{y_k \in \{0,1\}, u_k \in \{0,1\}, T_k \geq 0\} \forall k, \; q \geq 0 \quad (32)$$

$$v_{kj}^h \geq 0 \; \forall k \; \forall j \; \forall h. \quad (33)$$

The formulated problem is an MILP problem. The first five constraints are the same as the optimal multicasting/multicasting problem. The variable v_{kj}^h can be relaxed, in this case, since the optimal solution will return a binary value for v_{kj}^h. MT j is forced to receive with bit rate R_{S} from a candidate MT $k \in \mathcal{L}$ or from any other MT k on a certain hop on SR. Assume that MT j can receive from multiple MTs k with bit rate R_{S}; thus, it will consume the same amount of energy if it downloads the whole content from one of the K MTs or if it downloads fractions of the content from each of them, so that, finally, it collects all the content as forced by (21). As a result, one of the optimal solutions will return a binary value for v_{kj}^h. The sixth constraint (30) determines whether MT k transmits on SR, i.e., when $u_k = 1$ or not, i.e., when $u_k = 0$. Note that $\sum_{h=1}^{H} v_{kj}^h \leq 1$, since MT k might send the content only once on one hop to MT j. The seventh constraint (31) ensures that MT j cannot receive from MT k by setting v_{kj}^h to zero, if the available bit rate $R_{S,kj}$ is lower than R_{S}. The last constraints (32) and (33) determine the types of the variables.

The optimization problem can be solved for a given R_{S}. After solving the problem, the achievable multicasting bit rate, in some obtained groups, can be higher than the threshold value R_{S}, depending on the worst channel conditions between the transmitting MT and the other MTs in the group. Hence, we adapt the obtained transmission bit rates in the groups accordingly.

1) Problem Hardness:

Theorem 3: The simplified energy-aware multicasting/multicasting problem with multihop cooperation on SR is NP-complete.

Proof: Consider a relaxed version of the simplified multicasting problem in which the BS transmits with the same bit rate as the MTs. This can be obtained by setting $R_{L,k} = R_{\mathrm{S}}$ in constraints (22) and (23). In this case, the total energy consumption of the MTs can be expressed as $S_{\mathrm{T}}[K^L(E_{\mathrm{Rx,L}}(R_{\mathrm{S}})/R_S) + (K - K^S)(E_{\mathrm{Tx,S}}(R_{\mathrm{S}})/R_{\mathrm{S}}) + (K - K^L)(E_{\mathrm{Rx,S}}(R_{\mathrm{S}})/R_{\mathrm{S}})]$, where K^L is the number of MTs that receive the content on LR, and K^S is the number of MTs with degree 1, i.e., the MTs that receive the content only; thus, $(K - K^S)$ represents the number of transmitting MTs on SR.

If we further assume that the energies consumed to receive on LR and SR are the same, i.e., $E_{\mathrm{Rx,L}}(R_{\mathrm{S}}) = E_{\mathrm{Rx,S}}(R_{\mathrm{S}})$, then the total energy consumption of the MTs can be expressed as $S_{\mathrm{T}}[(K - K^S)(E_{\mathrm{Tx,S}}(R_{\mathrm{S}})/R_{\mathrm{S}}) + (K)(E_{\mathrm{Rx,S}}(R_{\mathrm{S}})/R_{\mathrm{S}})]$. Now, it is obvious that to minimize the overall energy consumption of the MTs, the number of transmitting MTs on SR, i.e., $(K - K^S)$ should be minimized, or in other words, K^S (MTs that receive only without transmitting) should be maximized. This problem becomes similar to the maximum leaf spanning tree (MLST) which is NP-complete [33]. The MLST problem is defined as follows. Given a graph G, an MLST is a spanning tree that has the largest possible number of leaves (nodes of degree 1) among all spanning trees of G. Moreover, it is straightforward to show that a solution for the relaxed simplified multicasting/multicasting problem can be verified in polynomial time; thus, the problem is NP-complete.

As a result, it is obvious that the general simplified multicasting/multicasting problem in which the BS has higher power capabilities than the MTs and can adapt its transmission bit rate to further minimize the energy consumption of the MTs is NP-complete. ■

Corollary 1: The optimal energy-aware multicasting/multicasting problem in which the multicasting bit rates on LR and SR are optimally allocated is NP-complete.

2) Suboptimal Algorithm (SA): The simplified multicasting problem gives the minimum energy consumption for a given R_{S};

however, the best value of R_{S} is not known. Thus, Algorithm 1 is applied accordingly to find the value of R_{S} that minimizes the total energy consumption. In Algorithm 1, a range of typical values for the bit rate R_{S} on SR is considered, depending on the SR technology characteristics. We assume that this range is limited to a small number, as in most wireless standards, and varies from a minimum value R_{Smin} to a maximum value R_{Smax} (e.g., WLAN IEEE802.11g supports eight bit rates between 6 and 54 Mb/s). The optimization problems can be solved in parallel for each value of R_{S}. Finally, the best solution that minimizes objective function (29) is chosen. In some groups, the achievable multicasting bit rate can be higher than the threshold value R_{S}, depending on the worst channel conditions between the transmitting MT and the other receiving MTs in the group. Hence, we adapt the obtained transmission bit rates in the groups accordingly. We should also highlight that as R_{S} increases, the transmission time decreases, which decreases the energy consumption of the transmitting and receiving MTs. However, as R_{S} increases, the transmission range of the MTs decreases since only very close MTs can decode the content reliably, which increases the required number of transmitting MTs in the network. Consequently, it is obvious that neither a very small nor a very high value of R_{S} is favored.

Algorithm 1 SA

Step 1. Select the minimum, the maximum, and the increments of R_{S}, i.e., R_{Smin}, R_{Smax}, and R_{Sinc}, respectively.
Step 2. Assign the possible values of $R_{\mathrm{S}} = [R_{\mathrm{Smin}}, R_{\mathrm{Smin}} + R_{\mathrm{Sinc}}, R_{\mathrm{Smin}} + 2 \cdot R_{\mathrm{Sinc}}, \ldots, R_{\mathrm{Smax}}]$.
Step 3. For each assigned value of R_{S}, solve the presented optimization problem in Section III-C.
Step 4. Choose the solution of the optimization problem that gives the minimum objective presented in (29). The selected solution determines the MTs that receive on LR and the MTs that transmit and receive on SR.
Step 5. Choose the optimal multicasting bit rate on SR within each obtained group and distribute the content accordingly.

D. Optimal Unicasting/Multicasting and Optimal Multicasting/Unicasting Problem Formulations

Having formulated the optimal unicasting/unicasting problem and optimal multicasting/multicasting problem, it becomes straightforward to deduce the optimal unicasting/multicasting and optimal multicasting/unicasting problems by using the constraints that model the communication scheme of interest.

Corollary 2: The optimal energy-aware unicasting/multicasting and multicasting/unicasting problems with multihop cooperation on SR are NP-complete.

E. Complexity Analysis

All the integer variables in this work are binary. The complexity of an MILP formulation having binary integer variables depends on two main factors. First, it highly depends on the number of binary variables in the problem formulation since the worst-case complexity is on the order of $O(2^b)$, where b is the number of binary variables. The other important factor is the performance of the LP relaxation of the optimization formulation with respect to the optimal integral solution. For example, all multicasting constraints whether on LR or SR [e.g., (22)–(26)] obviously deviate the LP relaxation from the optimal integral solution as the values of y_k and v_{kj}^h would be chosen so as to lower Z_k and C_{kj} as much as possible. This increases the required number of branch-and-bound operations to reach the optimal integral solution. Note that such constraints are not needed whenever unicasting is used on LR or SR.

The required number of binary variables is $K + H \cdot K^2$ in all formulations except for the simplified multicasting/multicasting formulation where it is $2K$. Moreover, depending on the value of R_{S}, a significant number of v_{kj}^h is also set to zero, which simplifies the choice of the MTs that transmit on SR, i.e., the u_k variables. In summary, we are able to decrease the number of binary variables from $K + H \cdot K^2$ in the optimal multicasting/multicasting formulation to a number lower than $2K$ in the SA mutlicasting/multicasting formulation.

IV. Interference Avoidance

Unicasting communication is more expensive than multicasting communication in terms of the required number of orthogonal resources. In the unicasting/unicasting case, K orthogonal resources are required on LR and SR to distribute all the content. Utilizing frequency resources increases the required bandwidth, which is scarce, and utilizing time resources can increase the delay, if the required number of time slots, to deliver the content, is high. Using multicasting communication is a better design alternative in terms of resource savings. Thus, the multicasting/multicasting problem has gained increased research attention in the literature [3], [4], [8].

Most multicasting problems in mobile ad hoc networks (e.g., [34] and references therein) try to optimize multicasting tree construction without taking interference into account as the formulations in Section III. Moreover, many of the proposed formulations, in the literature, cannot accommodate interference avoidance constraints, particularly those that use the decision variables that model all possible paths in the network, e.g., [4]. Interference is not taken into account since it can be assumed that the MTs can transmit on orthogonal channels, which can be frequency channels or time slots. Since MTs transmit using the same wireless technology on SR, we will devise two interference avoidance schemes and discuss the complexity of each.

In the first scheme, it can be assumed that there is a limited number f_r of orthogonal resources (frequency channels or time slots) on SR links. Based on this, only up to f_r MTs can only transmit on SR to avoid interference between the groups. This interference avoidance constraint can be represented as follows:

$$\sum_{k=1}^{K} u_k \leq f_r. \tag{34}$$

Constraint (34) can be directly integrated in the simplified multicasting/multicasting problem formulation, whereas it should be integrated along with (30) in the rest of the problem formulations. Note that this interference avoidance scheme is suitable for both unicasting and multicasting on SR. If the number of orthogonal channels is limited on SR, then more MTs should receive the content on LR.

In the second scheme, one can exploit the spatial reuse by allowing the MTs that are out of the transmission range of one another to transmit at the same time. In this case, the interference contention graph should be modeled as a set of cliques in which only one MT, within a clique, is allowed to transmit at a given instance of time. A clique is composed of the set of MTs that mutually interfere with each other, if they transmit at the same time. This also accounts for the case where a receiving MT can hear transmitting MTs, which causes interference at the receiving MT; in this case, the transmitting MTs are considered as interfering MTs. A maximal clique is a clique that cannot be extended by including one more adjacent MT, that is, a clique that does not exclusively exist within the MTs' set of a larger clique. Listing all maximal cliques in a graph $G(\mathcal{K}, A)$, where A represents the set of links between the interfering MTs, can be achieved in polynomial time with a worst-case complexity of $O(a(G)|A|)$, where $a(G)$ is the arboricity of the given graph and is bounded as follows: $|A|/(|\mathcal{K}|-1) \leq a(G) \leq \sqrt{|A|}$ for a connected graph [35].

Assume that the obtained set of cliques is $\mathcal{C}$ upon the termination of the algorithm presented in [35]. Thus, within each obtained clique $C \in \mathcal{C}$, only one MT is allowed to transmit at the same time or hop assuming that all transmissions are synchronized, i.e., the MTs that transmit on a given hop transmit at the same time. To model this constraint, variable u_k should be replaced with variable u_k^h to indicate on which hop MT k is transmitting. This change requires also the modification of constraint (30) to

$$v_{kj}^h \leq u_k^h \; \forall h \; \forall k \; \forall j. \tag{35}$$

Finally, the interference avoidance constraint with spatial reuse can be modeled as

$$\sum_{k \in C} u_k^h \leq 1 \; \forall h \; \forall C \in \mathcal{C}. \tag{36}$$

It is obvious that the interference avoidance with spatial reuse is more computationally complex than the first proposed scheme since the required number of binary variables increases by $(H-1)K$; this is obtained by changing the binary variable u_k to u_k^h to model the constraint accurately. Moreover, the number of constraint increases due to (35) and (36).

V. Heuristic Algorithms

This section presents a heuristic algorithm to obtain polynomial-time solutions for the different proposed LR/SR communication strategies. The proposed algorithm performs different functionalities for unicasting and multicasting on LR and SR, as shown in Algorithm 2.

Algorithm 2 Heuristic Algorithm

Step 1. Consider the set of MTs, $\mathcal{K}$, without the BS and let $n = 1$.
Step 2. Build a connection graph among the MTs as follows. For each MT $k \in \mathcal{K}$, connect it to all other MTs $j \in \mathcal{K}$ satisfying the condition $R_{\mathrm{S},kj} \geq R_{\mathrm{S}}$.
Step 3. For each obtained connected subgraph $m = 1, \ldots, M$, execute:

- for multicasting on SR, the 2-approximation algorithm for the MLST problem proposed in [36]. This determines the minimum number of transmitting MTs on SR and ensures that all MTs receive the content.
- for unicasting on SR, the MST problem using Prim's algorithm [31].

Step 4. Decompose each subgraph m into trees of maximum depth H hops:

a. Place the transmitting MTs that have leave nodes of degree 1, in T'. Then, choose the one that has the worst channel condition on LR and place it in T, i.e., $T = \{k^* \in T', k^* = \arg\min_{k \in T'} R_{L,k}\}$.
b. Determine the parents of k^* of depth $H-1$ from k^* and place them in T.
c. Choose the MT that has the best channel condition on LR in T, i.e., $k^n = \arg\max_{k \in T} R_{L,k}$.
d. From MT k^n determine all MTs in the subgraph that are within depth H from MT k^n and place them in T_n. Place MT $k^n \in \mathcal{L}$ and let $n = n+1$.
e. Disconnect all MTs that are of depth $H+1$ from MT k^n, thus, forming new subgraphs. Repeat steps (a)–(d) on the newly obtained subgraphs until all MTs in original subgraph m are processed and placed in trees of maximum depth H.

Step 5. Upon obtaining the trees T_n in which the MTs that receive on LR are k^n do:

- for unicasting on LR: the BS sends the content to each MT $k \in \mathcal{L}$ with bit rate $R_{L,k}$.
- for multicasting on LR: the BS sends the content to all MTs $k \in \mathcal{L}$ with bit rate $\min_{k \in \mathcal{L}} R_{\mathrm{L},k}$.
- for unicasting on SR: MT k sends the content to MT j with bit rate $R_{S,kj}$, if there is a connection between MT k and MT j in T_n.
- for multicasting on SR: MT k sends the content to MT j with minimum bit rate $\min_j R_{S,kj}$, if there is a connection between MT k and MT j in T_n.

Step 6. Repeat Steps 1–5 for various transmission ranges of the MT, i.e., for $R_{\mathrm{S}} = [R_{\mathrm{Smin}}, R_{\mathrm{Smin}} + R_{\mathrm{Sinc}}, R_{\mathrm{Smin}} + 2 \cdot R_{\mathrm{Sinc}}, \ldots, R_{\mathrm{Smax}}]$. Choose the solution that corresponds to the minimum energy consumption of the MTs.

We have shown in Section III-A1, that the optimal unicasting/unicasting problem is similar to the kHMST problem. It is shown, in [37], that the general kHMST has no approximation algorithm with a guaranteed approximation ratio unless $P = NP$. Some works have proposed an approximation algorithm for a restricted kHMST problem such as assuming that the graph is complete [38]. The connection costs, in this work, depend on distance and shadowing of the channel. As a result, the graph is not complete, and thus, the problem cannot be approximated with an approximation algorithm that has a guaranteed performance. Similarly, the optimal multicasting/multicasting problem has all the constraints of the kHMST problem in addition to more complicated constraints that are responsible for finding the optimal transmission bit rates on LR and SR, and thus, the problem has no approximation algorithm in polynomial time. As a result, we will propose heuristic solutions for the different LR/SR communication strategies. Then, using extensive simulations, we can evaluate the performance of the heuristic algorithm with respect to the optimal solution since we are computing it as well.

For multicasting on SR, we will propose a heuristic solution for minimizing the number of transmitting MTs on SR, which minimizes the energy consumption of the MTs, as shown in Section III-C.1. To achieve this goal, we will exploit the best known 2-approximation algorithm for a restricted MLST [36] to minimize the number of transmitting MTs on SR. However, to cope with the proposed system model, we will adapt the restricted MLST algorithm to integrate the role of the BS and restrict the number of hops.

For unicasting on SR, the proposed heuristic algorithm adapts the MST algorithm, presented in [31], to integrate the role of the BS and restrict the number of hops.

The proposed heuristic algorithm, presented in Algorithm 2, can be summarized as follows. First, consider the set of MTs, i.e., $\mathcal{K}$, without the BS. Then, constraint (31) determines whether MT k can connect to MT j or not, which depends on the given transmission bit rate R_{S} and the achievable bit rate between MT k and MT j, i.e., $R_{\mathrm{S},kj}$. Based on this constraint, an undirected graph can be built, since the bit rates are assumed to be symmetric. This determines which MTs can send the content to the MTs that can receive it correctly. As a result, several disconnected subgraphs can exist whose union form up all the MTs.

For multicasting on SR, each obtained subgraph can be defined by $G'(V', A')$, where V' is the set of MTs within this subgraph, and A' is the adjacency matrix representing the connections between the MTs. The aim is to choose the minimal number of MTs, i.e., $S'_m \subseteq V'$, that should transmit on SR subject to the constraint that each MT $k \in V' - S'_m$ can receive the content from an MT in S'_m, as shown in constraints (19) and (20). This problem is exactly similar to the MLST problem. Thus, the 2-approximation algorithm for the MLST problem, presented in [36], is applied for each obtained subgraph, which determines the transmitting MTs on SR.

For unicasting on SR, each obtained subgraph can be defined by $G'(V', A')$, where V' is the set of MTs within this subgraph, and A' is the adjacency matrix that contains the connection costs. For unicasting on SR, the MST is applied for several considered connection costs. First, MST is applied assuming that the connection costs are the real consumed energies that are inversely proportional to $R_{S,kj}$. In this case, an MT connects itself with the neighboring MT that it views with the highest transmission bit rate, which increases the number of hops significantly. In the second case, each $R_{S,kj} \geq R_S$ is replaced with R_S in the adjacency matrix. When applying Prim's algorithm, it starts with a parent MT k and starts assigning its children MTs to which it should transmit the content. It assures that all MTs within bit rate R_{S} from MT k are connected to the same parent MT k before moving and assigning a new parent that connects other MTs. This strategy reduces the number of hops in the obtained MST. Among these two options for the connection costs, the solution that gives the minimum energy consumption will be finally chosen.

After obtaining the subgraphs for either multicasting or unicasting on SR, which results in different sets of transmitting and receiving MTs. The fourth step of the algorithm is applied, which clearly shows how to divide the obtained subgraphs into trees T_n of depth at most H. The fifth step of the algorithm shows how to determine the transmission bit rates on LR and SR within the obtained trees T_n according to the used LR/SR communication strategy.

Various transmission ranges of the MTs will be considered since each transmission range results in a different solution. If $R_{\mathrm{S}} = R_{\mathrm{S,min}}$, the MTs can connect to each other with low bit rates. Thus, if MST and MLST are applied, the required number of transmitting MTs is much lower than the case where $R_{\mathrm{S}} = R_{\mathrm{S,max}}$, where only very close MTs can communicate. Finally, the solution that results in the minimum energy consumption for the MTs will be chosen.

The proposed heuristic algorithm has a computational complexity of $O(K^2)$ for all LR/SR communication strategies. To obtain the MST, Prim's algorithm is applied using the adjacency matrix, which requires $O(K^2)$ operations [31]. To obtain the MLST, the 2-approximation algorithm is applied, which also requires $O(K^2)$ operations [36]. It can be easily seen that all the other proposed steps of the algorithm require, at most, $O(K^2)$ operations. Since the algorithm is applied for a small number of iterations for the various R_{S} values, which are within a small range as explained in Section III-C2, the computational complexity of the proposed heuristic algorithm is on the order of $O(K^2)$.

VI. Performance Results and Analysis

To assess the performance of the proposed approaches, we set up the following simulator. A number of MTs are deployed within a predefined square area with the BS located at the left-bottom corner of the area. We have captured the general energy consumption expressions that are a function of the various transmission bit rates. However, there are limited studies, in the literature, that associate for a typical range of transmission bit rates, the corresponding energy consumed during transmission and reception for various LR and SR technologies. For example, the works in [27] and [28] present lookup tables for the energies consumed during transmission only for a limited range of bit rates. Due to the lack of datasheets that relate the transmission and reception energies, for various LR and SR technologies, at different transmission bit rates, we will follow the model of the work in [26], which was verified using experimental measurements. According to [26], the energy consumed per unit time can be considered almost constant for various

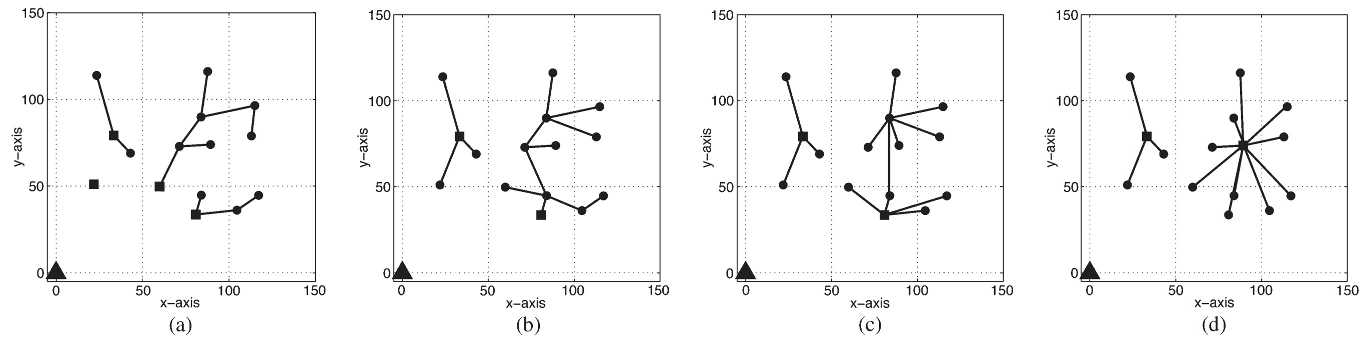


Fig. 3. Content distribution and resulting groups for $K = 15$ requesting MTs. The triangle represents the BS. The square represents an MT that receives on LR. The circle represents an MT that transmits and/or receives on SR; the link between sending and receiving MTs is marked by a solid line. (a) Optimal uni./uni. (b) Optimal multi./multi. (c) SA multi./multi. (d) SA multi./multi. with interference avoidance for $f_r = 2$.

transmission bit rates using adaptive rate control. A study conducted in [26] for the measurements of the energies consumed per second by an MT to receive on an LR 3G technology and to transmit and receive on an SR IEEE 802.11 technology using adaptive rate control has shown that $E_{\mathrm{Rx,L}}(R) = 1.8$ J/s, $E_{\mathrm{Rx,S}}(R) = 0.925$ J/s, and $E_{\mathrm{Tx,S}}(R) = 1.425$ J/s. The thermal noise σ^2 is considered to be 10^{-7} mW. The channel parameters are: $\kappa = -31.54$ dB, $\nu = 3.71$, and $d_0 = 10$ m, and we assume h_{dB} to be a zero-mean Gaussian random variable with $\sigma^2_{h_{\mathrm{dB}}} = 13.29$ dB as in [24]. Thus, $h_{k'j}$ follows a lognormal distribution, which represents a slow-fading (shadowing) channel model. The content size S_{T} is set to 8 Mb. The value of R_{Smin} is set to 1 Mb/s, R_{Sinc} is set to 1 Mb/s, and R_{Smax} is set to 12 Mb/s. The optimization problems are solved using the CPLEX solver, which performs standard-LP-based branch-and-bound techniques [39].

A. Snapshot Network Scenario Results

Here, we assume that the MTs are arbitrarily distributed in a 150 m $\times$ 150 m area. The maximum number of allowed hops is set to $H = 4$ hops.

Fig. 3 presents snapshot results for the optimal unicasting/unicasting solution, the optimal multicasting/multicasting solution, and the SA multicasting/multicasting solution for two cases: with no limits on the available number of orthogonal resources f_r (as if all channels are orthogonal) and with interference avoidance assuming only two orthogonal resources on SR, i.e., $f_r = 2$. The first proposed interference avoidance method, presented in Section IV, is used in such a small area. Results demonstrate that the MTs that have the best combination of channels on LR and SR are those that receive and distribute the content.

Fig. 3(a) shows that whenever unicasting is used on LR and SR, more MTs receive the content from the BS since they are receiving with the maximum possible transmission bit rate and are not sacrificing some of their energies to receive with a lower bit rate, which happens whenever multicasting is used on LR. For unicasting on SR, an MT consumes an additional energy to transmit to each MT on SR; however, it uses the maximum possible bit rate with the other MTs. The optimal unicasting/unicasting solution achieves around 33% of energy consumption saving compared with the noncooperative unicasting case on LR and 45% compared with the noncooperative multicasting case on LR.

Fig. 3(b) and (c) shows that whenever multicasting is used on LR and SR, fewer MTs receive on LR since the LR multicasting bit rate is limited by the worst transmission bit rate among MTs $k \in \mathcal{L}$. However, with multicasting on SR, an MT consumes one transmit energy to transmit the content to all MTs in its group, which, in turn, can benefit from receiving with higher transmission bit rates. Thus, less MTs will receive on LR, and more MTs will receive on SR. The optimal LR multicasting bit rate is 5 Mb/s for the optimal solution and the SA solution with no limits on f_r and 4 Mb/s for SA with $f_r = 2$. Whereas, the LR multicasting bit rate is 1 Mb/s in the traditional approach with all MTs receiving on the LR multicasting channel. The energy savings are significant, ranging from 51% for SA multicasting/multicasting with $f_r = 2$, 60.2% for SA multicasting/multicasting, and 66.7% for the optimal multicasting/multicasting solution compared with the noncooperative multicasting case on LR. The SA solution without limits on f_r is very close to the optimal solution since the same set of MTs receive the content on LR with some variations in the groups and the optimal chosen bit rates on SR.

B. Effect of the Available Number of Orthogonal Resources

In this and the following sections, we assume that the MTs are arbitrarily distributed in a 500 m $\times$ 500 m area with the BS at the bottom-left corner.

Fig. 4 summarizes the effect of the number of available orthogonal resources f_r on the total energy consumption averaged over 250 snapshots with different MTs' locations and channels assuming $H = 4$ hops. Interference avoidance is applied on the SA multicasting/multicasting formulation. Fig. 4 shows that increasing f_r achieves more energy reduction gains as K increases, since the closer MTs can be grouped together to benefit from higher multicasting bit rates on SR, which decreases the transmit and receive energies of the MTs.

Fig. 4 also shows that up to a total of six and eight orthogonal resources on all hops, for $K = 20$ and $K = 30$ MTs, respectively, are needed to achieve maximum energy consumption reduction gains. This shows that multicasting is an efficient solution in terms of the required orthogonal resources. Moreover, minimal gains are achieved for high values of f_r such

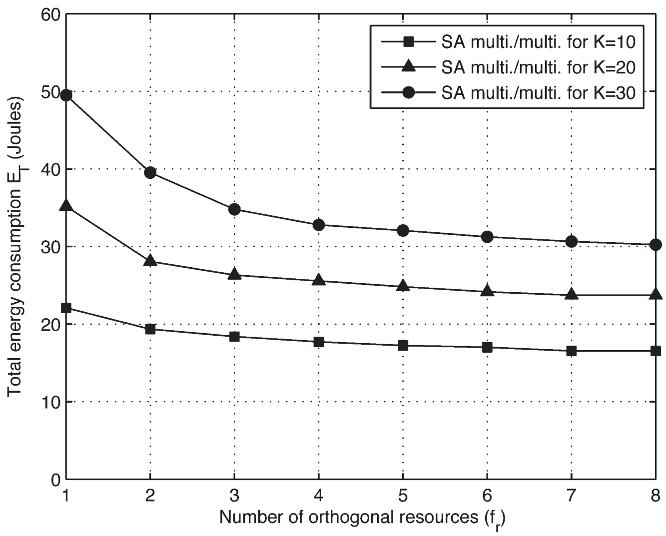


Fig. 4. Total energy consumption versus the number of orthogonal resources f_r on SR for $H = 4$ hops.

as increasing the number of orthogonal resources from six to eight. Thus, the proposed multicasting formulation can give efficient solutions with a small number of available orthogonal resources.

C. Average Energy Consumption Results

This section presents the energy consumption performance, averaged over 250 snapshots, for all proposed approaches, and it shows the effect of increasing the number of hops H on SR.

Fig. 5 presents the total energy consumption of the MTs versus K assuming that $H = 1$ hop for optimal unicasting/unicasting, optimal unicasting/multicasting, optimal multicasting/unicasting, optimal multicasting/multicasting, and SA multicasting/multicasting. In all these cases, it is assumed that there are no limits on f_r. Fig. 5 also shows the performance of the noncooperative unicasting and multicasting cases on LR. It is interesting to highlight that in traditional content distribution approaches, such as unicasting on LR (the BS unicasts the content to each MT with a customized rate based on its channel condition), the MTs consume less overall energy compared with multicasting on LR (all MTs receive on one LR multicasting channel); however, unicasting on LR requires much more radio resources.

Fig. 5(a) compares the proposed optimal approaches with the noncooperative cases, whereas Fig. 5(b) compares the optimal approaches only on a smaller axis scale for clarity. It is obvious that the proposed approaches achieve significant energy consumption gains compared with the noncooperative cases. It is also obvious that unicasting on LR is more energy efficient than multicasting on LR, whereas multicasting on SR is more energy efficient than unicasting on SR due to the aforementioned reasons in Section VI-A. Thus, the performance of the approaches in terms of ascending order in energy consumption saving is 1) optimal multicasting/unicasting, 2) optimal unicasting/unicasting, 3) SA multicasting/multicasting, 4) optimal multicasting/multicasting, and 5) optimal unicasting/multicasting. Thus, optimal unicasting/multicasting has the best

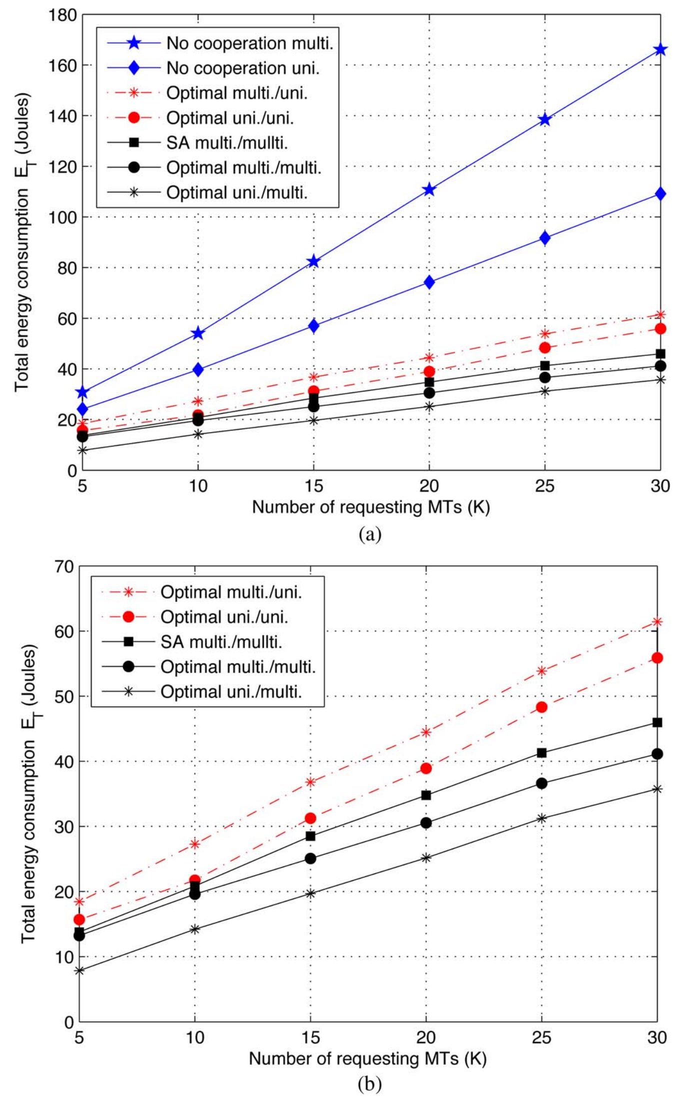
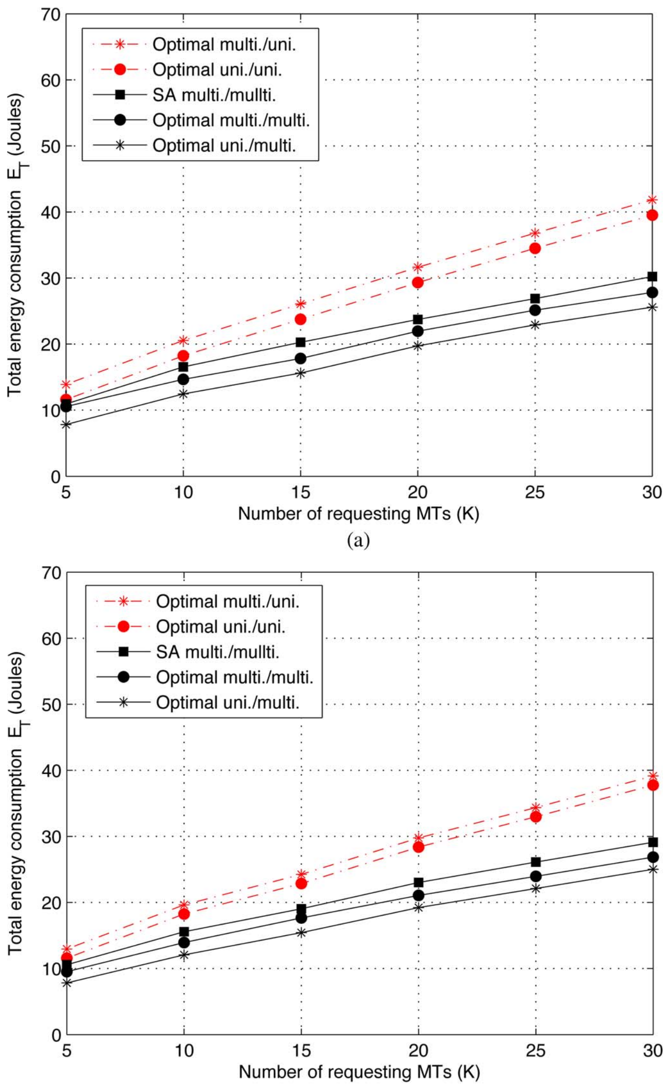


Fig. 5. Total energy consumption versus the number of requesting MTs K for $H = 1$ hop.

performance; however, its drawback with respect to multicasting on LR is the higher required number of LR resources.

Results demonstrate the effectiveness of the proposed cooperative approaches compared with both traditional content distribution approaches. For example, the worst performance, which is that of optimal multicasting/unicasting, achieves energy reduction savings reaching up to 43.74% and 63.03%, at $K = 30$ MTs, compared with noncooperative unicasting and noncooperative multicasting on LR, respectively. Whereas, the best performance, which is that of optimal unicasting/multicasting, achieves energy reduction savings reaching up to 67.5% and 78.8%, at $K = 30$ MTs, compared with noncooperative unicasting and noncooperative multicasting on LR, respectively. Moreover, the SA multicasting/multicasting solution demonstrated a very close performance to the optimal multicasting/multicasting solution where the difference in the energy consumption is, at most, 14%. The energy savings increase as K increases since the probability of having closer MTs that can communicate with high bit rates, in the given area, increases, which decreases the energy consumption of the MTs.



(a)

(b)

Fig. 6. Total energy consumption versus the number of requesting MTs K. (a) $H = 4$ hops. (b) $H = 8$ hops.

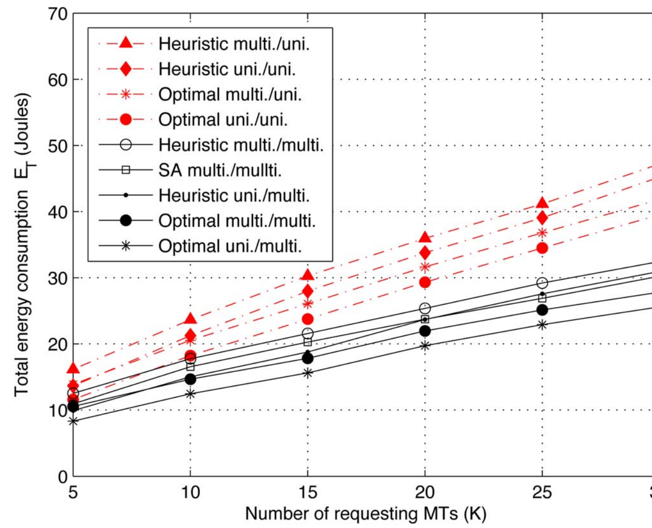


Fig. 7. Total energy consumption versus the number of requesting MTs K for $H = 4$ hops.

Fig. 6(a) shows the effect of increasing the number of hops to $H = 4$ hops on the total energy consumption of the MTs. It is obvious that much higher gains can be achieved. For example, the optimal multicasting/unicasting energy consumption savings reach up to 61.67% and 74.82%, at $K = 30$ MTs, compared with noncooperative unicasting and noncooperative multicasting on LR, respectively. Whereas, the optimal unicasting/multicasting energy reduction savings reach up to 76.56% and 84.6%, at $K = 30$ MTs, compared with noncooperative unicasting and noncooperative multicasting on LR, respectively.

The interesting observation is that whenever the number of hops H increases on SR, it does not make a big difference anymore whether unicasting or multicasting is used on LR. This is due to the fact that when the number of hops H increases, the MTs can cooperate with each at a closer distance and, thus, will favor SR cooperation compared with receiving on LR. Moreover, the optimal solution will favor the MTs that are close to the BS to receive on LR for both unicasting and multicasting on LR, if the available number of hops on SR is enough for that. Since the MTs that are close to the BS have nearly equal bit rates, then only little energy consumption scarification will happen at some MTs, which results in nearly equal performance for unicasting and multicasting on LR as the number of hops H increases. However, whether to use unicasting or multicasting on SR makes a big difference even when the number of hops increases.

We have shown that increasing the number of hops from one to four achieves significant energy consumption savings; however, increasing the number of hops to eight will not make a big difference, as shown in Fig. 6(b), which has nearly equal results to Fig. 6(a). This definitely depends on the considered area. For example, if the considered area is increased beyond 500 m × 500 m, then increasing the number of hops will definitely be of more value and will result in higher gains, however, at the cost of obtaining higher computationally complex optimal solutions, as will be demonstrated in Section VI-F.

Fig. 7 presents the results of the heuristic solutions with respect to the optimal solutions. It is clear that the heuristic solution achieves a good performance with respect to the optimal solution where the maximum gap is less than 20% for the various LR/SR communication strategies. Note that the results of the noncooperative case are the same as those in Fig. 5(a).

D. Average Energy Consumption Results in Mobile Scenarios

The formulated problems assume that the bit rates, on LR and SR, are static during the content download and distribution process; this is very logical for small contents such as a file (e.g., breaking news, advertisement, etc.). However, for large content sizes, such as videos (e.g., live sport games), the content download might take a long time. Given that the MTs might be moving, then the achieved bit rates on LR and SR are subject to change. Thus, periodic reconfiguration of the LR and SR distribution strategies needs to be done to adapt to the network changes due to mobility. To maintain a good performance of the proposed approaches, the reconfiguration interval should become smaller as the MTs' environment changes faster; this directly depends on the moving speeds of the MTs. Here, we assume that the content is divided into several chunks. At each reconfiguration period, a chunk will be distributed by recomputing the proposed solutions.

The formulated optimization problems should be adapted to the dynamics of the network, and thus, the problems should be dynamically solved. For instance, the network information can be periodically collected, after each chunk distribution, to find the new achieved bit rates, on LR and SR, while optimizing the distribution of the next chunk.

We consider that the MTs are moving according to the random walk model with mobility reflection [40]. The MT speeds are randomly selected from a uniform distribution between 0 m/s and a maximum speed m_s m/s.

1) Impact of Reconfiguration Interval: We assume that the MTs are moving with slow to medium speeds uniformly distributed between 0 and a maximum of 6 m/s. Fig. 8(a) shows the average total energy consumption of 20 MTs versus the reconfiguration interval. It also shows the performance of mobile scenarios compared with static scenarios where the network parameters are fixed, and consequently, the optimal solution does not degrade during content distribution. It is shown that as the reconfiguration interval duration decreases, the energy consumption of the MTs decreases too, however, at the cost of more computational complexity since the solution is recomputed more times compared with the case when the reconfiguration interval is larger.

2) Impact of Moving Speed: Fig. 8(b) shows the effect of the maximum moving speed of the MTs on the total energy consumption assuming 20 MTs. In this case, the reconfiguration interval is set to 4 s. As the moving speed of the MTs increases, the performance degrades, and the energy consumption of the MTs increases. Thus, the proposed approaches perform well for static to slow-moving scenarios (e.g., MTs in a café or an airport).

The optimal solution considering the mobility of the MTs can be obtained, if instantaneous reconfiguration of the solution is done every time the network changes. This requires the collection of the needed network information at the instance when the network changes, which increases the complexity of the solution and questions its practicality. However, theoretically, finding the optimal solution is feasible. For high-mobility scenarios (e.g., vehicular networks), the proposed approaches are not expected to give high gains compared with the non-cooperative case, as shown in Fig. 8(a) and (b), unless a very small reconfiguration interval is chosen, which results in higher computational complexity.

Although some energy is required for information collection, we assume that the energy consumed for bit rate evaluation with the neighboring MTs is small relative to the actual energy that the MTs will consume when they start transmitting and receiving the content. This can be motivated by the fact that the time scale for content download and sharing is generally much larger than that for information collection, which is usually performed using pilot signals that are on the order of a few bytes. Moreover, in mobile environments, the MTs

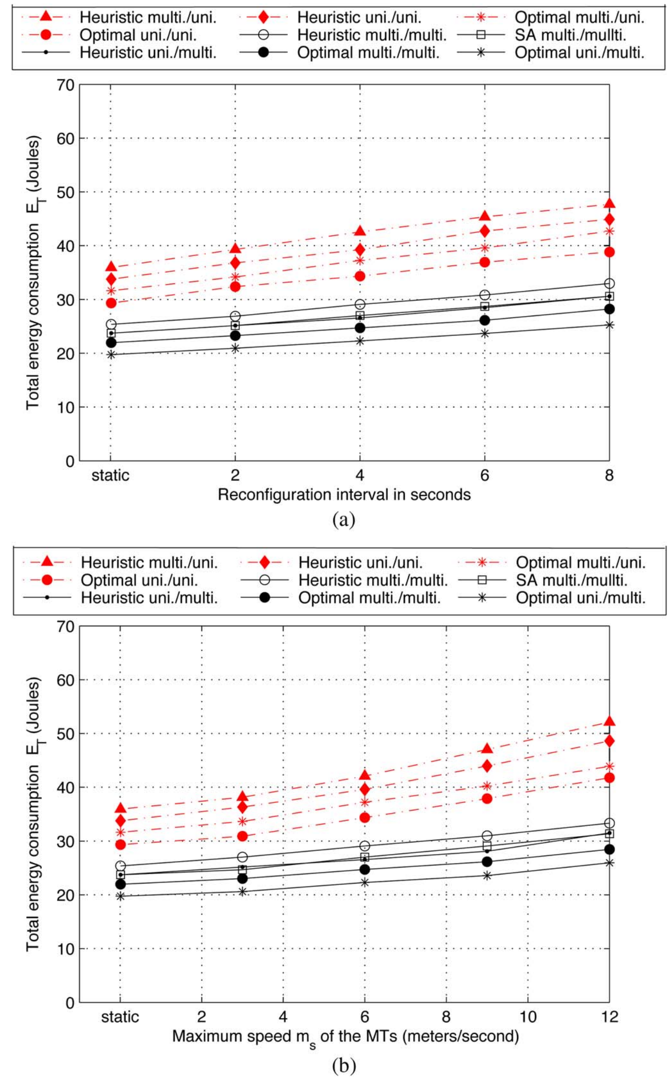


Fig. 8. Effect of mobility on the the energy consumption of the MTs for $H = 4$ hops. (a) Average total energy consumption of 20 MTs versus the reconfiguration interval. (b) Average total energy consumption of 20 MTs versus the maximum moving speed m_s of the MTs.

exchange roles in receiving and distributing the content due to the update of the LR/SR content distribution solution at the reconfiguration intervals, as the LR and SR channels vary due to mobility. Thus, in large content downloads, on average, the neighboring MTs will consume a nearly equal amount of energy during the content download and distribution process. However, imposing strict battery limit constraints for each MT is a very interesting extension and an important future research direction that is based on the formulations and analysis of this work.

To maintain the practicality of the proposed solution regarding the information collection and the computational complexity, we can see that our proposed mobility handling approach best fits static to slowly moving environments in which the network slowly changes. This also decreases the probability of a transmitting MT leaving and entering its group/cluster within a small reconfiguration period. To complement the proposed mobility handling approach against any arising uncertainties within the reconfiguration period, the following practical considerations are integrated.

- Transmitting MT leaving and entering a group: An upper layer control protocol should be implemented in practice to facilitate periodic sensing of the link availability between MTs. When a transmitting MT leaves the network, the MTs in its cluster would immediately contact the BS to proceed with the download process on the LR. Then, if an MT detects the transmitting MT again with a connection better than the LR link, it can switch the connection back to it. Note that this fast degradation or improvement in the bit rates between the communicating entities occurs only in highly mobile environments, which is not inline with our proposed system model.
- MT leaving: If an MT that is not transmitting any content leaves the network (e.g., battery dying or deciding to quit the download process), then no action should be taken since no other MTs are depending on it. In the next reconfiguration period, the solution will be recomputed without considering the MTs that left the network.

E. Statistics on the Transmitting and Receiving MTs and the Required Resources

Fig. 9(a) and (b) presents statistics for the average frequency count of the number of receiving MTs from the BS and the transmitting and receiving MTs on the four hops for $K = 30$ MTs, assuming multicasting and unicasting on LR, respectively. Note that an MT that is counted only once as a transmitting MT might be transmitting to more than one MT on SR. In other words, the figure is not showing the number of transmissions, it is showing the number of MTs that are transmitting. However, it is obvious that for unicasting on SR, the number of transmissions or required orthogonal resources is equal to the number of MTs that are receiving on a certain hop. Whereas for multicasting, the number of required orthogonal resources is equal to the number of transmitting entities (MTs/BS) on a certain hop. For example, one orthogonal resource is required to deliver the content from the BS to around four MTs in the optimal multicasting/unicasting case, as shown in Fig. 9(a), whereas five orthogonal resources are required to deliver the content from the BS to five MTs in the optimal unicasting/unicasting case, as shown in Fig. 9(b).

Results show that the number of receiving MTs from the BS decreases when multicasting is used on LR compared with unicasting. With multicasting on LR, the worst bit rate of the receiving MTs on LR is used; thus, SR cooperation with high bit rates is favored to overcome the limited LR multicasting bit rate. Second, the number of receiving MTs from the BS depends, first of all, on whether multicasting or unicasting is used on SR. When unicasting is used on SR, the number of MTs that receive on LR is higher as previously explained in Section VI-A. Fig. 9(a) shows that the average number of receiving MTs on LR is around 3.5 for unicasting on SR and around 2 for multicasting on SR.

After receiving on LR, only few MTs transmit the content, in the first hop, to reach a notable subset of the MTs on SR. Then, a small subset of the receiving MTs, on the first hop, transmit

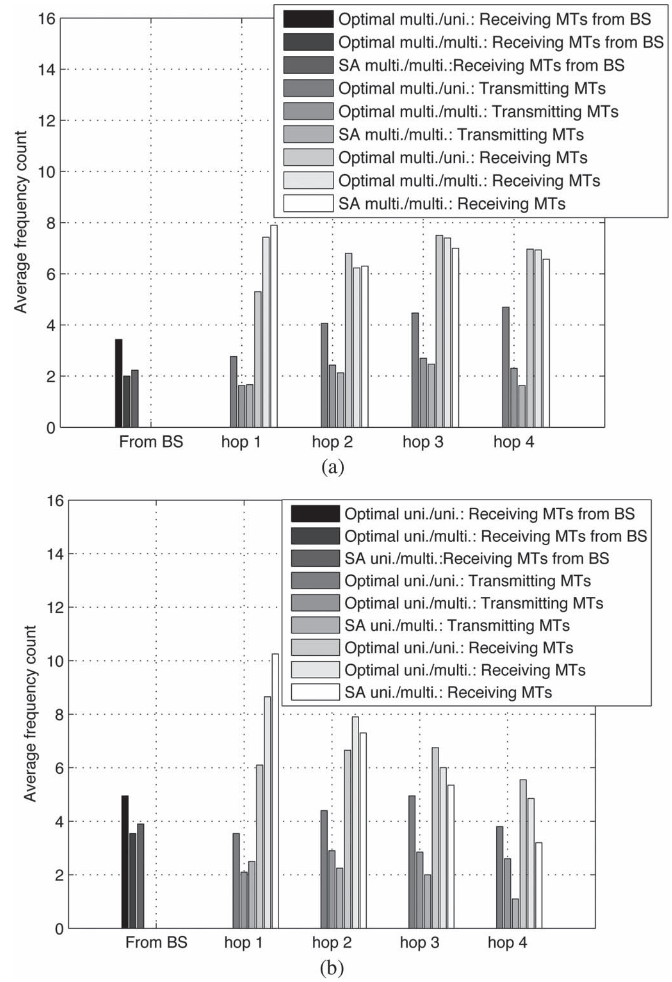


Fig. 9. Average frequency count of the number of receiving MTs from the BS and the transmitting and receiving MTs on four hops for $K = 30$ MTs. (a) Multicasting on LR. (b) Unicasting on LR.

the content to other MTs on the second hop and so on. It is also obvious that, for multicasting on SR, the number of transmitting MTs is always lower compared with unicasting on SR, which is expected.

For multicasting on SR, the total number of transmitting MTs on all hops does not exceed eight on average, with up to three transmitting MTs at the same time, which reveals the low required number orthogonal channels on SR. This has been also demonstrated in Fig. 4. However, for unicasting on SR, the minimum required number of orthogonal resources on SR is 25 obtained in the optimal unicasting/unicasting case as shown in Fig. 9(b) where, on average, five MTs receive on LR, whereas the remaining 25 MTs receive on SR. Thus, there is a significant resource saving for multicasting communication compared with unicasting communication on both LR and SR. The lowest required number of resources goes to the multicasting/multicasting solutions, which require around nine resources on LR and SR combined. For example, if the SA multicasting/multicasting solution is applied, then one orthogonal resource is required on LR and eight orthogonal resources are required on SR. This saves 70% of the required resources compared with traditional noncooperative unicasting schemes where 30 resources are required. Moreover, significant energy

TABLE II
CT OF THE OPTIMAL SOLUTIONS FOR $H = 1$ HOP

K	10	20	30
Optimal uni./uni. (sec)	0.018	0.026	0.046
Optimal multi./uni. (sec)	0.07	0.647	6.724
Optimal uni./multi. (sec)	0.087	130.302	1200
Optimal multi./multi. (sec)	0.734	529.966	3899.93
SA multi./multi. (sec)	0.058	0.069	0.089

TABLE III
CT OF THE OPTIMAL SOLUTIONS FOR $H = 4$ HOPS

K	10	20	30
Optimal uni./uni. (sec)	0.055	0.203	0.96
Optimal multi./uni. (sec)	0.115	2.12	16.3
Optimal uni./multi. (sec)	3.24	1625	7238
Optimal multi./multi. (sec)	20.45	3205	11240
SA multi./multi. (sec)	0.096	1.113	5.75

consumption gains can be achieved with the SA multicasting/multicasting solution, as shown in Fig. 6(a), which are 72.31% and 81.1%, at $K = 30$ MTs, compared with noncooperative unicasting and noncooperative multicasting on LR, respectively. Thus, the proposed cooperative schemes achieve significant energy consumption and resource savings.

In this paper, we have proposed four LR/SR communications schemes; hence, an important question that arises is: Which of the communication schemes should be used? The answer is that each of the communication schemes has its own pros and cons and is also sometimes limited by the used technology. The choice of a communication scheme depends on the objectives of the operator and the used technology. For example, based on the obtained results, multicasting on LR consumes less LR channels than unicasting; however, it is less energy efficient. However, multicasting on SR consumes fewer SR channels and is also more energy efficient than unicasting communication; however, multicasting is not standardized in all SR technologies.

Unicasting communication is standardized in all LR and SR wireless communications technologies. Multicasting communication has been recently standardized for LR wireless technologies such as 3G and 4G cellular networks by 3GPP as part of the Multimedia Broadcast/Multicast Service technical specifications; however, this is not the case for all SR wireless technologies; for example, Bluetooth supports unicasting on SR only, whereas other technologies, such as WLAN, can support either unicasting or multicasting.

F. Computational Complexity Analysis

The optimization problems are solved on the same platform using the CPLEX solver [39]. We have shown, in Section III-E, that the computational complexity of the optimal solution depends on the number of binary variables, in the problem, and on the gap between the LP relaxation and the optimal integral solution. Depending on the obtained computational times (CTs), we can determine which of these two factors has a bigger effect on the CT of a solution and which formulations can be efficiently solved in a small CT. Tables II–IV present the average CTs, in seconds, to obtain the optimal solutions for $H = 1$, $H = 4$, and $H = 8$ hops, respectively.

TABLE IV
CT OF THE OPTIMAL SOLUTIONS FOR $H = 8$ HOPS

K	10	20	30
Optimal uni./uni. (sec)	0.271	2.652	36.8
Optimal multi./uni. (sec)	0.757	31.497	531.238
Optimal uni./multi. (sec)	30.928	5092	20560
Optimal multi./multi. (sec)	333.659	12326.6	40853.6
SA multi./multi. (sec)	0.691	10.625	197.200

First, it is obvious that the gap between the LP relaxation and the optimal integral solution has a higher effect on the optimal solution compared with the number of integral variables since the SA multicasting/multicasting solution has a higher CT compared with the optimal unicasting/unicasting solution. The number of binary variables in the SA multicasting/multicasting solution is $2K$, whereas it is $K + HK^2$ in the optimal unicasting/unicasting solution. However, the multicasting constraint on LR in the SA multicasting/multicasting solution is increasing its computational complexity. Based on the obtained CTs, the problems can be ordered in terms of increasing order of complexity as follows: 1) optimal unicasting/unicasting; 2) SA multicasting/multicasting; 3) optimal multicasting/unicasting; 4) optimal unicasting/multicasting; and finally, 5) optimal multicasting/multicasting.

Second, as the number of hops H increases, the computational complexity of the optimal solution also increases since the problem size increases (i.e., number of variables, constraints, etc.). Table IV shows that for $H = 8$ hops, almost all problems become computationally complex at K greater than or equal to 30 MTs. However, we have shown, in Fig. 6(b), that minimal gains can be achieved by increasing the number of hops to $H = 8$ compared with $H = 4$ hops, as shown in Fig. 6(a). Thus, increasing the number of hops can be extremely computationally complex with minimal gains compared with a lower number of hops.

In this paper and at the beginning of each reconfiguration interval, the bit rates on the LR and SR channels are collected to compute the optimal solutions at the BS. While the BS is computing the solution, the network is kept static to find all the optimal solutions. When the solutions are found, the MTs move according to the random walk model, whereas the content is distributed from the BS to the MTs and among the MTs themselves. Then, the needed network information is recollected at the beginning of the next reconfiguration period. However, in real scenarios, the network does not stay static while the BS is computing the solution unless the CT of the solution is very small, i.e., on the order of milliseconds. Thus, depending on the CT of the solution, we can decide which of the optimal solutions can be proposed as online solutions.

The CT of the solution depends on the used platform for the simulations. In this paper, we have used a computer with 32 GB of RAM and a 3.4 GHz processor. However, in real networks, supercomputers are used at the BS, which are extremely computationally fast. Then, the solution of some optimal approaches such as optimal unicasting/unicasting and SA multicasting/multicasting, for small network sizes, might take milliseconds instead of seconds when using our platform. When the solution takes only milliseconds, it can be proposed as an online solution; otherwise, we have proposed a

TABLE V
CT OF THE OPTIMAL SOLUTIONS FOR $H = 4$ HOPS AND $f_r = 4$ ORTHOGONAL CHANNELS

K	10	20	30
Optimal uni./uni. (sec)	0.108	0.513	2.29
Optimal multi./uni. (sec)	0.287	3.04	38.62
Optimal uni./multi. (sec)	7.42	4832	17890
Optimal multi./multi. (sec)	62.5	10432	48754
SA multi./multi. (sec)	0.12	2.64	13.72

polynomial-time heuristic solution that can be used as an online algorithm with a verified performance with respect to the optimal solution as shown in Figs. 7 and 8.

The most computationally efficient solutions are the optimal unicasting/unicasting and the SA multicasting/multicasting solutions, which can be efficiently computed in less than 0.96 and 5.75 s, respectively, for $K = 30$ MTs assuming that the number of hops is $H = 4$ hops. As a result, they might be proposed as online solutions, using supercomputers, without the need of finding a heuristic solution. This is not the case for the optimal multicasting/multicasting solution, where a heuristic solution becomes necessary, since the CT is around 11 240 s. Thus, in this paper, we were able to overcome the very high complexity of some problems such as the optimal multicasting/multicasting solution by proposing suboptimal problems such as the SA multicasting/multicasting solution, which is computationally efficient while still achieving a close-to-optimal performance in terms of energy consumption reduction and resource saving.

Table V shows the effect of limiting the available number of orthogonal channels on SR to $f_r = 4$. Results show that the CT increases compared with the unconstrained case on f_r shown in Table III; this is expected since the constraint is an additional restriction on the optimal solution. Hence, we conclude that limiting f_r increases both the energy consumption of the MTs and the computational complexity of the solution.

VII. CONCLUSION

This paper has presented an optimal energy-aware cooperative approach for content distribution over wireless networks with multihop cooperation on SR. Several optimization formulations have been presented that model all possible LR/SR communication strategies. A suboptimal algorithm has been also proposed to solve the multicasting problem on SR with lower computations compared with optimal multicasting on SR, however, with a close-to-optimal performance. Moreover, interference avoidance methods have been discussed, and their comparative complexities have been analyzed. All the optimization problems are NP-complete except for the optimal unicasting/unicasting problem in which the number of hops is not controlled, i.e., can take any value. Thus, polynomial-time heuristic solutions with good performance with respect to the optimal solution have been also proposed to solve the problems for large network sizes.

Performance results have shown that multihop cooperation among the MTs decreases their energy consumption and the required orthogonal resources significantly compared with traditional transmission schemes from the BS. Several proposed formulations proved to be very computationally fast and, thus, can be proposed as online algorithms.

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