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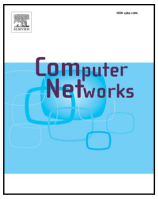

When are network coding based dynamic multi-homing techniques beneficial?

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ABSTRACT

Mechanisms that can cope with unreliable wireless channels in an efficient manner are required due to the increasing number of resource constrained devices. Concurrent use of multiple communications technologies can be instrumental towards improving services to mobile devices in heterogeneous networks. In our previous work, we developed an optimization framework to generate channel-aware transmission policies for multi-homed devices under different cost criteria. Our formulation considers network coding as a key technique that simplifies load allocation across multiple channels and provides high resiliency under time-varying channel conditions. This paper seeks to explore the parameter space and identify the operating regions where dynamic coded policies offer most improvement over static ones in terms of energy consumption and channel utilization. We leverage meta-heuristics to find different local optima, while also tracking the intermediate solutions to map operating regions above 3 dB and 5 dB. Our results show a large set of relevant configurations where high resource efficiency can be obtained with the proposed transmission mechanisms.

1. Introduction

Nowadays mobile devices are equipped with a multitude of heterogeneous wireless interfaces that offer diverse bandwidth, reliability, and latency at different energy and economic costs. In this scenario of convergence of heterogeneous radio access technologies, multi-homing allows end devices to be simultaneously connected to and exchange data on multiple network interfaces, thereby increasing reliability and quality of service (QoS) of content delivery [1].

Typically, only one interface is used at a time, chosen according to static, pre-defined priorities: use Wi-Fi if possible, 3G otherwise, and Bluetooth for specific applications. This approach is consistent with today's business model for mobile connectivity, but it is not efficient in terms of managing network resources, or decreasing economic costs [2]. The interface to use should be chosen according to application and user requirements, as well as device and network context.

Current proposals, recently reviewed in [3], include network centric [4–7], user centric [8–12] and hybrid [13,14] approaches that trigger vertical handovers in heterogeneous wireless networks using a variety of techniques, e.g., stochastic linear programming [4], game theory [5], multiple-attribute decision making [15,16], grey relationship analysis [10], as well as concepts borrowed from economic modelling like profit [12], surplus [11], or utility functions [7]. Context-aware frameworks for vertical handovers have also been proposed [17–20]; however, they do not consider simultaneous use of more than one radio technology, which is a common limitation present in network selection work [21,22].

The emergence of multi-homing and the feasibility of unicast communication over multiple paths [23] opens up the possibility to use different interfaces simultaneously. In [24], the authors propose a scheme for choosing the access technology to use for each new flow upon arrival partitioning the flows over multiple radio access technologies. A framework for simultaneous use of 3G and WLAN by multi-homed devices is proposed in [25], considering the specificities of multilayer HTTP and video traffic, but the approach separates the traffic into multiple flows and makes a static allocation of those flows. These and similar proposals provide little or no adaptability to the inherent channel quality variations of wireless systems [26–31].

Adaptive resource allocation algorithms that choose which data to send/request through each available interface based on network conditions, traffic load, available energy, among other constraints are thus instrumental to leverage the full potential of converged heterogeneous wireless communications [32–34]. We note

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that none of these works provide a framework for exploring the parameter space and evaluating achievable gains, nor do they consider network coding exploring opportunistic transmissions in the context of multiple paths in converged heterogeneous wireless networks with time-varying channels.

Network coding, initially proposed in [35], constitutes a disruptive paradigm that relies on mixing (coding) packets end-to-end or at intermediate nodes in the network rather than storing and forwarding them [36,37]. Random linear combinations are sufficient to achieve the maximum capacity of a network with probability exponentially approaching 1 with the code length [38] while attaining minimum delay [39,40]. From a receiver's perspective, it is no longer crucial to focus on gathering specific packets, but to gather enough linearly independent coded packets to recover the original information. This enables network coding to exploit multiple routes and/or network topologies seamlessly by dynamically shifting traffic between different paths, without concerning about coordination or packet scheduling problems. By exploring redundant network capacity, network coding reduces the need for complex management schemes, allows decentralised operation, and increases the robustness and resilience to topology/network changes and even link failures [38,41].

For transmissions in packet erasure channels, network coding provides robustness against packet losses and highly dynamic network conditions [36,38,42,43]. These traits make network coding very appealing for the volatile environments typical of heterogeneous wireless networks, especially when data may be transmitted simultaneously using different technologies as is enabled by multihoming.

Network coding is a block-coding operation where each block represents a generation. Other block-based codes used on packet erasure channels such as Automatic Repeat reQuest (ARQ) error-control codes [44], although achieving optimal throughput, have increased delay [36], and end-to-end Forward Error Correction (FEC) codes [45] do not achieve the optimal throughput due to the inherent redundancy adaptation to the end-to-end loss rate [36]. Digital fountain codes, such as Luby Transform (LT) codes [46] or Raptor codes [47] which are based on LT codes, low-density parity-check (LDPC) codes [48], turbo codes [49] and even Reed-Solomon codes [50] are examples of FEC codes. Usually, large block sizes are required to maximize capacity which add extra delay; less delay comes with the expense of a less efficient code. As FEC codes are used end-to-end, since intermediate nodes do not perform coding operations and confine themselves to relay packets, in [51] the authors propose the use of network-embedded FEC; however, nodes need to wait until sufficient packets are received for decode and further re-encode of a new data segment which adds extra delay to the system, while network coding would allow the immediate decode and re-encode of each packet.

Recent work on network coding has considered the use of multiple interfaces to improve Quality of Experience [52] with an economical cost objective and to minimize completion time of a file transfer [53]. In [54] our goal was to leverage network coding techniques optimising how to share load among the available interfaces between multi-homed devices over heterogeneous, time-varying wireless networks. Thereby we focused on a user-centric approach, formulating and solving a resource allocation problem for deciding when and under which conditions the offered traffic load should be transmitted on each available path. The numerical results proved that dynamic allocation policies using network coding improved resource usage efficiency by reducing energy consumption and/or channel utilization in some selected (and specific) scenarios.

In this article we extend and generalise that work by evaluating the actual potential impact of the proposed optimal policies. This work uses Simulated Annealing (SA) meta-heuristics to efficiently explore the parameter space and fully understand the advantages of dynamic allocation policies that adapt to the volatile channel characteristics; we compare their performance with the use of static policies, as are common in state-of-the-art devices, identifying under which operating conditions the reduction of energy consumption and channel utilization are most significant.

The rest of this article is organized as follows. Section 2 summarizes from [54] our mathematical framework for the problem, the static and dynamic allocation policies for heterogeneous wireless networks, and the metrics for performance evaluation. Section 3 presents our meta-heuristics to explore the parameter space. In Section 4 we present the best operating regions obtained for the performance of the proposed policies using numerical evaluations. In Section 5 we discuss the results, and Section 6 presents our conclusions.

2. Framework

We consider the problem of transmission of data packets from a source to a destination in a time-slotted system, where two independent channels are available[1]. Both source and destination can be relay nodes in a network. Our framework determines the amount of offered traffic load that should be sent on each channel. At each time slot, the source can transmit random linear network coded packets [38] through both channels (sending a different coded packet in each), one channel, or can decide not to transmit in that time slot. Given that packets arrive randomly at the sender, we consider an online network coding approach [37,55].

We assume an independent Gilbert–Elliott model for the channel [56,57]. Fig. 1 illustrates the scenario. We consider that each channel i can transmit using a combination of a set of modulation and (physical-layer) coding pairs, $\mathcal{M}_\rangle$. $M_{ij} \in \mathcal{M}_\rangle$ represents the jth available modulation and physical-layer coding pair available to channel i. $D(M_{ij})$ represents the fraction of useful information bits in a slot when transmitting with M_{ij}. Packet erasure (loss) probabilities on the ith channel for the good and bad channel state for modulation $M_{i,\,j}$ are represented by $e_{(i,g,M_{ij})}$ and $e_{(i,b,M_{ij})}$, respectively. The probability of channel i to remain in state $c \in \{b,\ g\}$ is given by $p_c^{(i)}$.

We assume that a genie indicates the joint channel state $C = (c_1, c_2)$ of the two channels, i.e., the probabilities of packet loss in each channel, at each time slot. However, the event of a packet loss is not known *a priori* to the genie.

We define $Pr_{(i,C,M_{ij})}$ and $\alpha_{(i,C,M_{ij})}$ as the probability of transmission through channel i during the joint channel state C using M_{ij} and the fraction of the data to be transmitted through channel i during the joint channel state C using M_{ij}, respectively. π_C constitutes the stationary probability of the joint channel state C, which can be easily determined through standard finite Markov chain techniques using $p_g^{(i)}$ and $p_b^{(i)}$ for $i = 1, 2$. The stationary probabilities π_g and π_b for each channel are obtained by:

$$\pi_g^{(i)} = \frac{1 - p_b^{(i)}}{2 - p_g^{(i)} - p_b^{(i)}};\ \pi_b^{(i)} = \frac{1 - p_g^{(i)}}{2 - p_g^{(i)} - p_b^{(i)}}. \tag{1}$$

The utilization of channel i in our system is given by

$$U_i([Pr_{(i,C,M_{ij})}]) = \sum_{M_{ij} \in \mathcal{M}_\rangle, C \in \{b,g\}^2} Pr_{(i,C,M_{ij})} \pi_C. \tag{2}$$

We define the total channel utilization of the system as $U = \sum_i U_i$, although other metrics can be used as cost functions for our optimization problem, e.g., minimizing the maximum of the U_i's.

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[1] This framework can easily be generalized to more than 2 channels.