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# Modeling tools to evaluate the performance of wireless multi-hop networks

Hakim Badis, Abderrezak Rachedi<sup>1</sup>

*University Paris-Est (UPEM)  
Gaspard Monge Computer Science Laboratory (LIGM UMR8049)  
Cité Descartes, 77454 Marne-la-Vallée, France  
{badis, rachedi}@u-pem.fr*

## Abstract

Recently, multi-hop communication has been introduced in next generation wireless networks to extend the service coverage area and to improve the wireless transmission capacity. In this chapter, we study several modeling tools mainly used to evaluate the performance of wireless multi-hop networks. We investigate three aspects of modeling tools: 1) stochastic modeling based on Markov-chain, 2) conflict graph particularly graph coloring, 3) asymptotic approaches for large-scale networks. For each tool, two physical communication systems are investigated: Single-Input Single-Output (SISO) and Multi-Input Multi-Output (MIMO). In addition, we illustrate how each tool contributes in the performance evaluation with particular emphasis on throughput and network capacity.

*Keywords:* Wireless Multi-hop networks, Modeling tools, Performance evaluation, MIMO

## 1. Introduction

A wireless multi-hop network can be viewed as a set of nodes able to communicate with each other directly or beyond their transmission range by using nodes as relay points acting as routers. Multi-hop communication has several advantages such as: interference reduction, spectrum reuse increase, radio coverage extension, traffic load balancing, and energy consumption reduction. These advantages make multi-hop communication more popular, and several kinds of networks are based on it such as Mobile Ad hoc Networks (MANETs) [1], Vehicular Ad hoc Networks (VANETs) [2, 3], Wireless Sensor Networks (WSN) [4], Wireless Mesh Networks (WMNs) [5], and so on. Their application range varies from civilian use to disaster recovery and military use. Recently, this technology has become a promising solution for the next generation wireless communication systems. It is considered in the standardization process of next-generation mobile broadband communication systems such as 3GPP LTE-Advanced [6], IEEE 802.16j (mobile WiMax) [7], and IEEE 802.16m [8]. For example, Mobile Multi-hop Relaying mechanism (MMR) is integrated into intermediate nodes to forward the traffic from mobile stations (MSs) to the base station (BS). In doing this, a wireless multi-hop network can effectively extend the service coverage and improve the overall capacity performance of a wireless communication system. Moreover, if each node is equipped with multiple antennas, and using point-to-point MIMO techniques to increase the rate of every individual link, then the overall capacity of the network increases linearly with the number of antennas per node [65, 66, 67]. For this reason, both single-antenna and multi-antenna communications in multi-hop networks are considered in this chapter.

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<sup>1\*</sup> Corresponding author. Tel.: +33-016-095-7737; fax: +33-016-095-7551.

<sup>1</sup> *E-mail address:* rachedi@u-pem.fr.

The performance of relay transmissions is greatly affected by the interference problem. Indeed, each node in a wireless multi-hop network can operate as transmitter, receiver or relay, which provides a tricky situation when several nodes in the same interference area transmit simultaneously. This situation, particularly the interference issue has a negative impact on the performance of wireless communication. The interference depends on several factors like the locations and the number of interfering transmitters. For instance, the geometry of the locations of the nodes is an important factor because it determines the signal to interference and noise ratio (SINR) at each receiver node. The interference at a receiver node is the sum of the signal powers received from all transmitting nodes, except its own transmitter. That is why, the Medium Access Control (MAC) layer protocol plays a key role since it is in charge of sharing and managing the access to the wireless link. Another important point where the interference has an indirect negative impact is the network capacity. The network capacity depends on several factors like network topology, nodes density, connectivity, mobility, etc.

Design of new MAC or routing protocols for wireless multi-hop networks is not an easy task particularly the performance evaluation step which is essential to know if the designed protocols work best. That is why modeling and simulation are used extensively to examine the network's behavior under different scenarios, and to optimize its performance before implementing these new protocols in the physical world. In the case of computer network design and optimization, software discrete-event-driven simulators are very important tools able to simulate complex networks, their architectures and their protocols.

In this chapter, we study different modeling tools mainly used in capacity evaluation for wireless multi-hop networks. We focus on a stochastic modeling based on Markov chain to evaluate the performance of MAC layer protocols. In addition, we present the relevant models based on the Conflict Graph (CG) particularly graph coloring and cliques in order to evaluate the network capacity. Finally, for large-scale networks, we discuss and analyze models based on an asymptotic approach. The main contribution consists in adapting each modeling tool from SISO to MIMO communication systems.

This chapter is organized as follows: Section 2 provides background on SISO and MIMO systems and gives a brief overview of wireless multi-hop networks: applications and challenges. Section 3 presents different modeling tools to evaluate the capacity performance of wireless multi-hop networks. The final section concludes this chapter.

## 2. Background

### 2.1. *Wireless Multi-hop Networks*

A wireless multi-hop network is a collection of fixed and/or mobile stations that communicate over a shared channel without requiring a fixed wireless infrastructure. In contrast to conventional cellular systems, there is no master-slave relationship between nodes such as base station to mobile stations. According to the communication range, communication between stations is performed by direct connection or through multiple hop relays. Figure 1 shows an example of one hop versus multi-hop communication. In figure 1.a, node A can communicate directly with any other node (B, C, D, and E) without any assistance of an intermediate or relayed node. However, in the case of multi-hop network (eg. Figure 1.b) node A needs at least one relayed node to reach nodes C, D, and E. In this network, a dynamic routing protocol is needed to ensure communication between nodes.

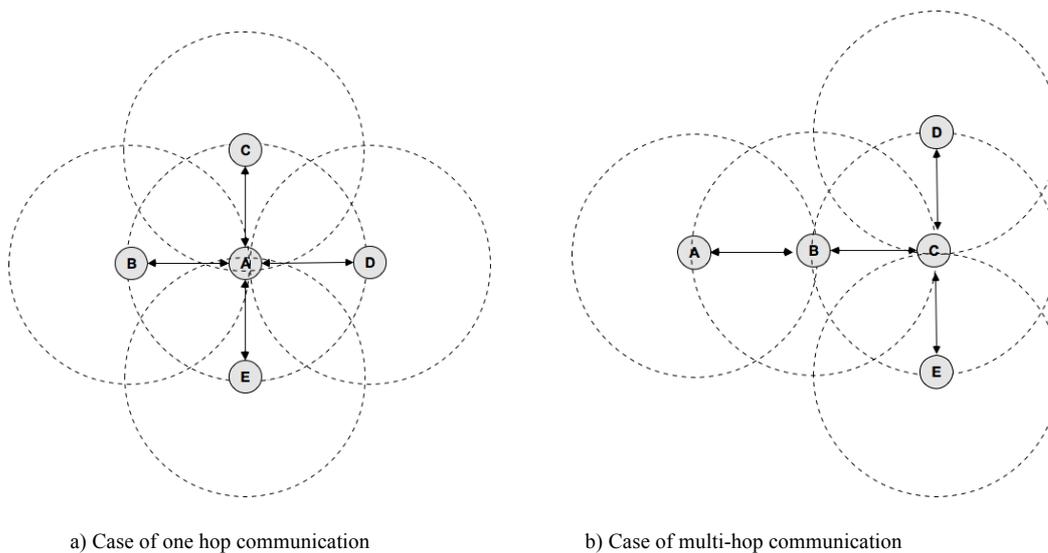


Figure 1. An example of one hop communication versus multi-hop communication

Several advantages of wireless multi-hop communication can be summarized as follows:

- *Interference reduction*: it is due to the reduction of transmission power ( $P_{TX}$ ) where nodes use close neighboring nodes to relay packets instead of increasing  $P_{TX}$ . This allows to reduce the number of competitor nodes sharing the same channel (link).
- *Spectrum reuse increase*: it is due to the short communication range where the spectrum can be reused more frequently. The spectral efficiency increases when the coverage area decreases [9]. Thus, the availability of frequency channels per unit area increases the system capacity.
- *Radio coverage extension*: it is guaranteed by relayed nodes through multi-hop communication, and it allows to reduce the nodes' isolation.
- *Traffic load balancing*: it is due to the different potential paths to reach the destination. This allows to avoid the congested nodes/links and to select non-congested nodes in order to ensure load balancing between them.
- *Power consumption reduction*: it is due to short-range communication where nodes reduce their power transmission and select relayed neighboring nodes to forward packets to their destination.

However, wireless multi-hop networks have some drawbacks such as: system complexity and security. The complexity is related to the design of an efficient routing protocol able to support a large number of nodes on the one hand, and a distributed MAC protocol able to face the hidden nodes problem on the other hand. The security issue is mainly related to the link vulnerability and end-to-end security services (authentication, confidentiality, integrity, and non-repudiation) guarantee.

Despite extensive research in networking, many challenges remain in the study of wireless multi-hop network including the development of MAC protocols that exploit the capabilities of advanced physical layer technologies like Multiple- Input Multiple-Output (MIMO) and Orthogonal Frequency-Division multiplexing (OFDM) [10]. That is why in this chapter we focus on the modeling tools able to design efficient performance models.

## 2.2. Examples of emerging wireless multi-hop networks

A transmission over multi-hop networks consists of multiple low-power transmissions of data over short distances. This approach enhances the network coverage, increases the network throughput through frequency reuse and reduces the total energy consumption of all participating nodes. This is why multi-hop relaying is being currently considered in the next generation wireless communication systems. Three emerging multi-hop networks have attracted growing attention: Vehicular Ad Hoc Network (VANETs), Wireless Sensor Networks (WSNs) and Multihop Cellular Networks.

### 2.2.1. Vehicular Ad Hoc Networks

VANET is a particular case of wireless multi-hop network, which has the constraint of fast topology changes due to the high node mobility [2, 3]. With the increasing number of vehicles equipped with computing technologies and wireless communication devices, inter-vehicle communication is becoming a promising field of research, standardization, and development. VANETs enable a wide range of applications, such as prevention of collisions, safety, blind crossing, dynamic route scheduling, real-time traffic condition monitoring, etc. Another important application for VANETs is providing Internet connectivity to vehicular nodes. Figure 2 shows an example of a VANET.

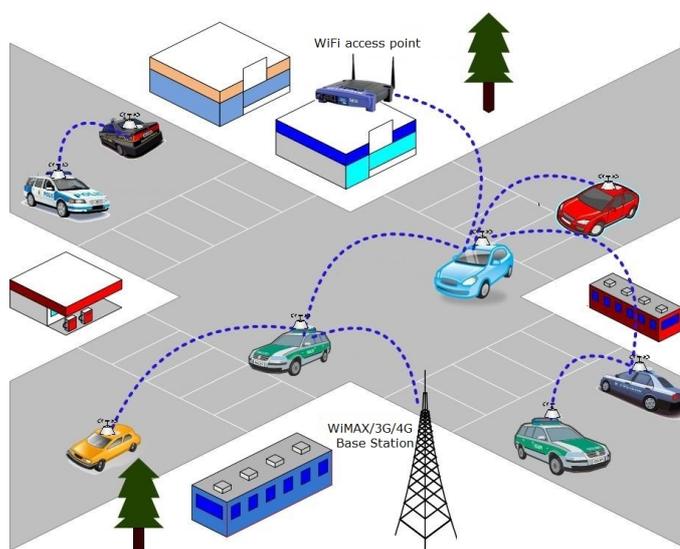


Figure 2. An Example of a VANET

### 2.2.2. Wireless sensor networks

WSNs are composed by low-power sensor nodes equipped with sensing board, processing, and wireless communication capabilities [4]. Sensor nodes collaborate to collect and to relay sensed information to a sink node using multi-hop communication. These networks can be applied in different applications such as healthcare, military, industrial, monitoring, tracking based on multimedia sensor and many other fields [68, 69]. Recently, IP-based sensor networks are attracting more attention, and are enabling the development of the Internet of things (IoT) [70]. However, energy consumption continues to remain a barrier challenge in many sensor network applications that require long lifetimes. Figure 3 shows an example of a WSN.

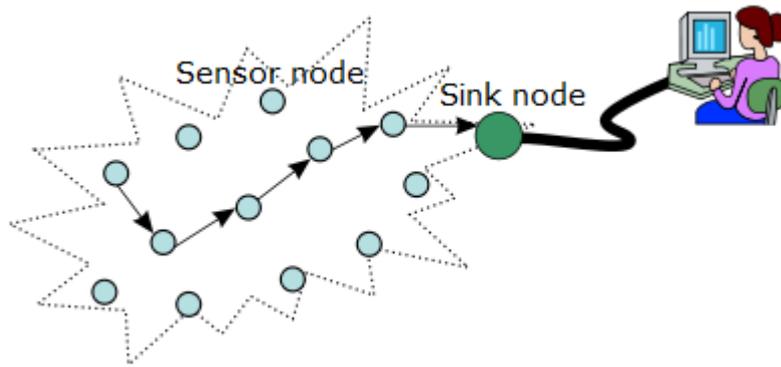


Figure 3. An Example of a WSN

### 2.2.3. Multihop Cellular Networks

Multihop Cellular Networks (MCNs) refer to the use of multihop relay nodes (cell phones and/or fixer relay stations) as intermediate nodes between a cell phone and its associated Base Station (BS) in the radio access network (RAN). This technology has the potential to offer extended cell coverage and improved the capacity of the cellular networks. Recently, relay technologies become a promising solution for the next generation wireless communication systems. It is considered in the standardization process of next-generation mobile broadband communication systems such as 3GPP LTE-Advanced [6], IEEE 802.16j (mobile WiMax) [7], and IEEE 802.16m [8]. Figure 4 shows an example of a MCN.

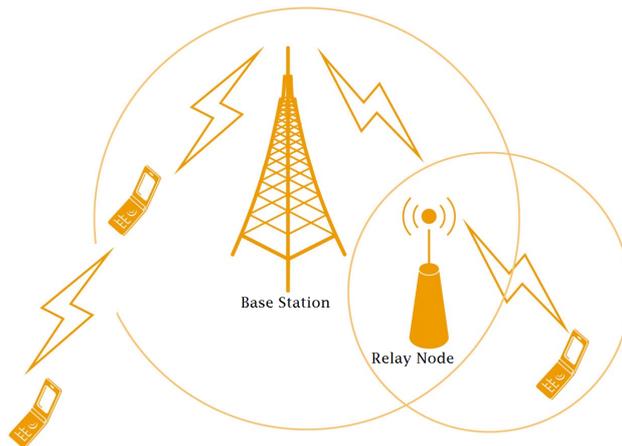


Figure 4. An Example of a MCN

### 2.3. SISO versus MIMO systems

In traditional single-antenna systems, called Single-Input Single-Output (SISO) systems, both transmitter and receiver are equipped with only one antenna each as illustrated in Figure 5. SISO systems are advantageous in

terms of simplicity and they are relatively easy to design and implement. They are used in several radio communication technologies like radio and TV broadcast, mobile phone networks (2G and 3G), local and personal wireless technologies (e.g. Wi-Fi and Bluetooth), sensor networks, etc. The channel capacity of such systems is given by Shannon's well-known formula [11]:

$$C = B * \log_2 \left( 1 + \frac{S}{N} \right)$$

where  $C$  is the capacity in bits per second,  $B$  is the bandwidth of the channel in Hertz, and  $S/N$  is the signal-to-noise ratio. Despite the significant progress made in improving the performance of SISO communication systems using OFDM and advanced coding and modulation schemes, they remain insufficient to meet the rapidly growing demands for high bandwidth and robustness in the next-generation networks.

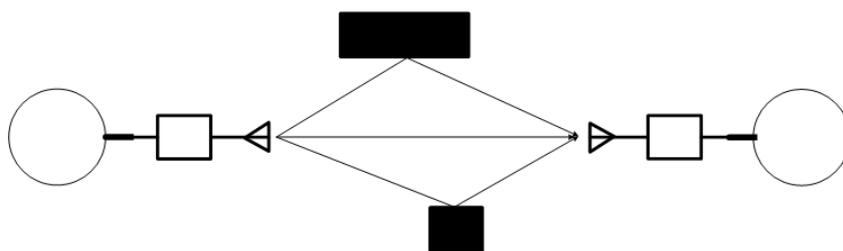


Figure 5. SISO system

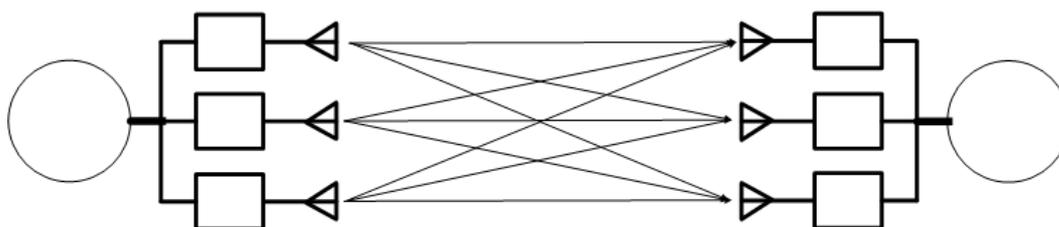


Figure 6. MIMO system

Recently, the use of multiple antennas at both transmitter and receiver has attracted much interest. This system is called Multiple- Input Multiple-Output (MIMO). Figure 6 shows an example of a MIMO system having three antennas at the transmitter and at the receiver. MIMO system is introduced in the new communication technologies standards like the Long Term Evolution (LTE) of the third Generation Partnership Project (3GPP) [12] the second generation of the Worldwide Interoperability for Microwave Access (WiMAX 2) [8], WiFi (IEEE 202.11n) [13], etc. This growing interest in MIMO systems is attributed to their various physical layer capabilities that allow:

- an increased channel capacity at higher signal-to-noise ratios by means of spatial multiplexing techniques. The new capacity of MIMO channel is given by [14, 15]

$$C = B * \log_2 \left( 1 + N \times M \times \frac{S}{N} \right)$$

where  $N$  and  $M$  are respectively the number of transmitting and receiving antennas;

- a decreased error rate by means of spatial diversity techniques;
- an improved signal-to-noise ratios using beamforming techniques.

However, these capabilities cannot be fully leveraged at the same time. The optimal strategy can be taken by the upper layers (MAC and routing) based on adapted cross-layer design approaches [16, 17, 18, 19, 20].

### 2.3.1. MIMO capabilities

By employing multiple transmitting antennas and multiple receiving antennas in conjunction with appropriately designed signal processing algorithms, MIMO has offered great benefits to wireless communications compared to conventional SISO systems. Indeed, a significant enhancement of communication quality at the physical layer has been observed in terms of link capacity, link reliability and communication range. Below, we briefly describe the physical layer capabilities.

**Spatial multiplexing** [14, 21, 22]. At the transmitter, the data sequence is split into  $N$  sub-sequences that are transmitted simultaneously using the same frequency band (see figure 7). At the receiver, the sub-sequences are separated by means of interference cancellation algorithms, e.g., linear Zero-Forcing (ZF) [23, 24], Minimum Mean-Squared-error (MMSE) detector [25], Maximum-Likelihood (ML) detector [14, 26], Successive Interference Cancellation (SIC) detector [27], etc. For a good error performance,  $M \geq N$  is required. Under the spatial multiplexing technique, the capacity of MIMO systems scales linearly with  $\min\{N,M\}$  [14]:

$$C = \min\{N, M\} \times B \times \log_2 \left( 1 + \frac{S}{N} \right)$$

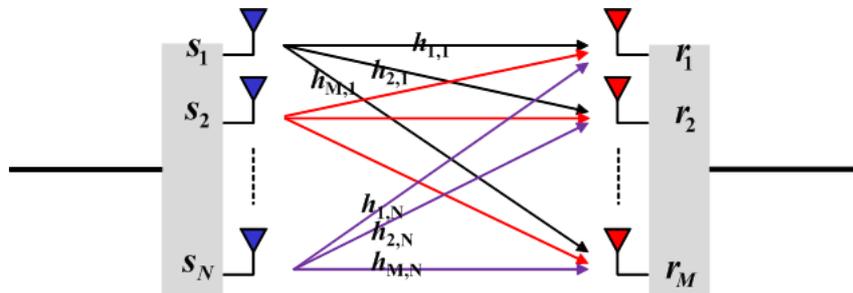


Figure 7. Spatial Multiplexing

**Beamforming** [28, 29, 30]. Due to antenna array geometry, radio frequency (RF) signals reach antenna elements at different times. By adjusting the initial phase of the RF signals on each antenna element, constructive superposition at the receiver can be achieved. From figure 8, beamformers can reject interference while omnidirectional antennas cannot improve SNR and system capacity.

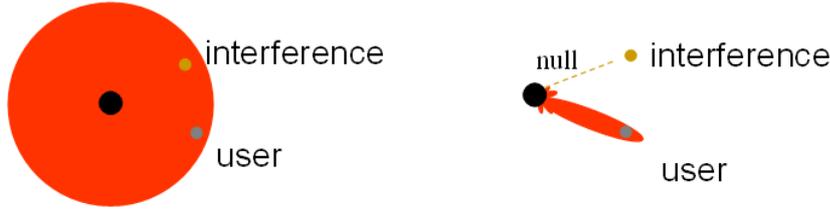


Figure 8. Beamforming

**Spatial Diversity** [31, 32, 33]. By sending/receiving multiple redundant versions of the same data stream and performing appropriate combining, the error rates decrease. When using diversity transmission, an appropriate pre-processing is needed to enable a coherent combining at the receiver. The well-known techniques are: Alamouti’s scheme [31], space-time trellis codes [32], and orthogonal space-time block codes [34]. When using diversity reception, an appropriate combining is needed. Various combining strategies are proposed [33]: Equal-Gain Combining (EGC), Selection Combining (SC), Maximum-Ratio Combining (MRC), etc.

2.3.2. *Modeling of SISO and MIMO channels*

The following notation will be used throughout the chapter. Scalars are given by normal letters, vectors by boldface lower case letters, and matrices by boldface upper case letters.

Under SISO systems and using OFDM, the channel can be expressed in the frequency domain as:

$$r(k) = h(k) \times s(k) + w(k)$$

where  $r(k)$  is the received symbol,  $s(k)$  is the transmitted symbol,  $w(k)$  is the Additive White Gaussian Noise (AWGN), and  $h(k)$  is a scalar value representing the gain and phase of the channel for subcarrier,  $k$ .

For MIMO systems, the received and transmitted symbols become vectors. Let us also assume that a transmitting station is equipped with  $N$  antennas and the receiving station is equipped with  $M$  antennas. The  $(M \times N)$  channel matrix  $\mathbf{H}(k)$  is written as:

$$\mathbf{H}(k) = \begin{bmatrix} h_{1,1}(k) & h_{1,2}(k) & \cdots & h_{1,N}(k) \\ h_{2,1}(k) & h_{2,2}(k) & \cdots & h_{2,N}(k) \\ \vdots & \vdots & \vdots & \vdots \\ h_{M,1}(k) & h_{M,2}(k) & \cdots & h_{M,N}(k) \end{bmatrix}$$

where the elements,  $h_{i,j}(k)$ , are each complex scalar representing the channel gain and phase from transmitting antenna  $j$  to receiving antenna  $i$ , for subcarrier  $k$ . The  $n^{\text{th}}$  column of  $\mathbf{H}$  is often referred to as the spatial signature of the  $n^{\text{th}}$  transmitting antenna across the receiving antenna array. The MIMO channel is given after the Fast Fourier Transform (FFT) as in [25].

$$\mathbf{r}(k) = \mathbf{H}(k) \times \mathbf{s}(k) + \mathbf{w}(k)$$

where  $\mathbf{r}(k) = [r_1(k) \ r_2(k) \ \dots \ r_M(k)]^T$  and  $\mathbf{s}(k) = [s_1(k) \ r_2(k) \ \dots \ r_N(k)]^T$ .

In order to estimate the SISO channel in OFDM systems, several methods [25] can be employed using time or frequency domain samples. These methods are extended to MIMO channel estimation like Least-Squares (LS) method or Minimum Mean-Squared-Error linear detectors.

### 3. Performance models

A performance model is a model that is used to assess and to evaluate the performance of a network. The development of any performance model follows the following modeling steps: 1) understanding the network properties, (2) model construction, and (3) verification and validation. In this section, we focus on stochastic modeling based on Markov-chain to evaluate the network performance in terms of throughput. The conflict graph models are presented to evaluate the network capacity. Finally, we present asymptotic capacity modeling to assess the upper and lower band network capacity. All these performance models are presented for SISO and MIMO systems.

#### 3.1. Stochastic modeling based on Markov-chain

##### 3.1.1. Preliminary and definitions

A Markov chain is a very powerful tool used in various fields including physics, economics, engineering, genetics, and more. It is widely used because of its simplicity, and flexibility. It's easy to model different systems with an arbitrary number of states and their transition matrix. It's used to model a dynamic system like wireless network that changes its states over time. Markov chains are classified into two kinds: continuous time Markov chains (CTMC) and discrete time Markov chains (DTMC). In DTMC, the state is allowed to change only at the discrete instants; that is not the case for CTMC where the state can change at any time.

In computer network area, the stochastic models are selected to represent uncertainty phenomena of the network (because it depends on many unknown factors) where its behavior varies as time advances.

In this subsection, we focus on two communication systems: Single-Input Single-Output (SISO), and Multiple-Input Multiple-Output (MIMO) both in wireless multi-hop networks. We present stochastic models based on Markov chain to evaluate the network throughput and MAC protocols performance based on IEEE 802.11.

##### 3.1.2. Case of SISO System

In carrier sense multiple access with collision avoidance (CSMA/CA) protocol, before node transmitting, it checks the state of the channel if it is busy or idle. If the channel is busy, the node waits until the channel becomes idle. If a collision happens, each node waits for a random time named "backoff". The backoff mechanism has a key role to avoid the interference between competitor nodes.

The well-known performance model based on DTMC to estimate the throughput at the MAC layer with IEEE802.11 is proposed by Bianchi [35]. This model assumes a single collision domain to reduce the complexity of the interference relationship. On the other hand, only one node among  $N$  competitor nodes can successfully transmit a packet at any time. It takes into account only the case of  $N$  active nodes called "saturated case" where these nodes always have a packet to transmit. Bianchi's model consists in modeling the behavior of backoff algorithm of a CSMA/CA in the saturated case as illustrated in figure 9.

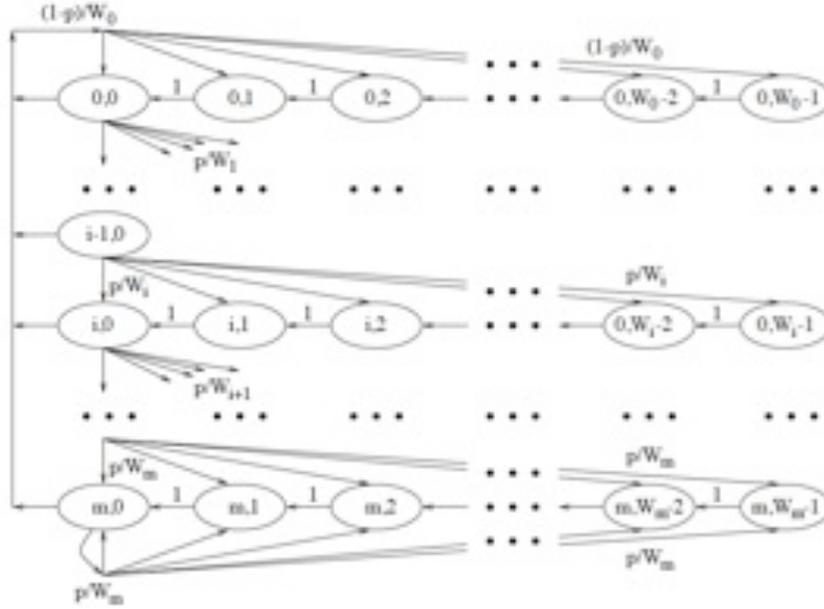


Fig. 9. Markov Chain model for backoff algorithm (case of SISO) [35]

The idea behind this model is to get the throughput expression (S) according to different probabilities such as probability that a transmission is successful ( $P_s$ ), and the probability that there is at least one transmission in a given slot time ( $P_{tr}$ ) where these probabilities depend on backoff parameters. Equation 1 shows the throughput expression [35]:

$$S_{SISO} = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr} P_s T_S + P_{tr} (1 - P_s) T_C}$$

where  $E[P]$  is the average packet payload size,  $T_S$  is the average time the channel is sensed busy,  $T_C$  is the average time the channel is sensed busy by each station during collision, and  $\sigma$  is the duration of one empty time slot.

The limits of this analytical model are based on two strong assumptions: saturated traffic, and single type of traffic assumptions. The typical traffic network is not only non-saturated, but also is heterogeneous. Many proposed models are based on non-saturated case, but without taking into account the heterogeneity of the traffic source [36, 37]. The main idea of these models consists in adding a new state representing the case where the buffer is empty without a significant change of the Bianchi's model.

Other proposed models taking into account the heterogeneity of traffic sources with distinct arrival rates are proposed in literature [38,39]. The added value of these models consists in the integration of the queuing model in order to evaluate the network performance with heterogeneous traffic sources. In the network, it's impossible to predict the human behavior and their communication requirements, that's why probability and stochastic processes particularly queuing theory are good candidates to predict the network behavior and to understand how traffic arrives. In these models the traffic arriving at the transmission queues is assumed as Poisson process.

However, all these models are proposed for legacy IEEE 802.11. Recently, other models are proposed for the IEEE 802.11 Enhanced Distributed Channel Access (EDCA) function [40, 41]. These models are applied only to the single collision domain where each link interferes with all other links as illustrated in figure 10.a. Figure 10.b illustrates the case of multiple collision areas which is a typical case of the multi-hop network.

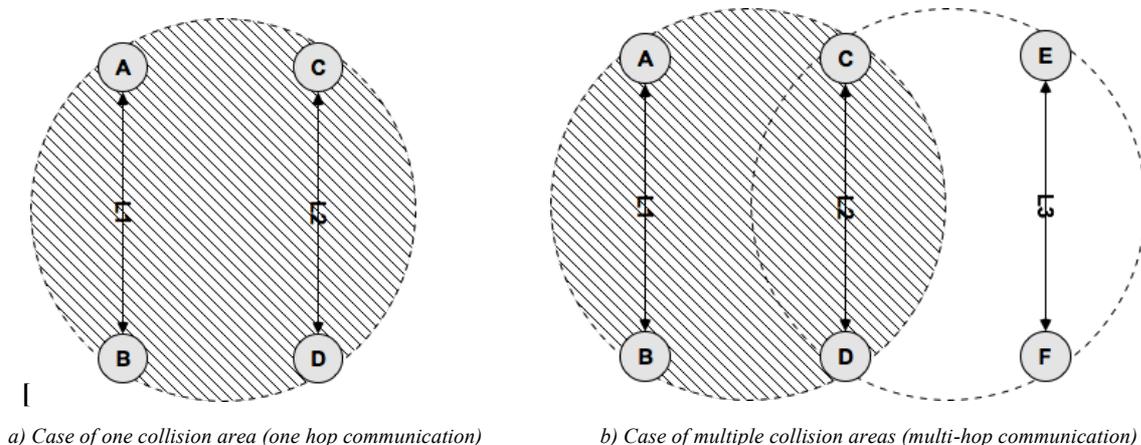


Fig. 10. Collision area in both cases: one-hop and multi-hop network

In other words, these models can be used in the case of one hop communication (eg. WLAN). Other models are proposed in the case of wireless multi-hop networks [42, 43, 44, 45, 46]. The adaptation of Bianchi’s model to the multi-hop network is mainly based on the integration of neighboring nodes’ environment in the throughput expression. In this kind of network the hidden-terminal problem may significantly impact the performance of MAC protocol [47]. That’s why in different proposed models each node has to take into account the parameters of its neighboring nodes such as: the probability to access a channel, the probability of failure, etc. For instance, a 3-dimension Markov chain is used to model the rate adaptation scheme in Mobile Ad hoc Networks (MANETs) [44]. This model evaluates the performance of dynamic rate adaptation scheme able to guarantee a tradeoff between throughput and relative fairness. The third dimension represents the rate that varies according to different parameters like link quality.

DTMC is not only used to evaluate the performance of the MAC layer protocol, but also to evaluate the impact of misbehaving nodes that are cheating on Binary Exponential Backoff (BEB) [48, 49]. The misbehaving nodes particularly the selfish nodes may maliciously manipulate BEB parameters in order to create unfairness situations, or to disrupt the network services.

### 3.1.3. Case of MIMO

Performance models based on DTMC for MIMO system do not require any change from those proposed for SISO systems if the used MAC protocol is independent from the underlying physical layer. For example, the MAC protocol CSMA/CA can be applied to both SISO and MIMO systems, and thus all the models previously developed for SISO systems (see section 3.1.2) remain valid. In literature, several works [50, 51, 52] maintain the same performance models based on the original or enhanced Bianchi's two-dimensional Markov chain.

The traditional MAC protocols do not fully exploit the capabilities of the MIMO physical layer like multiple simultaneous transmissions from multiple nodes in the same collision area. Thus, some recent works [16, 17,

18, 19, 20] on cross-layer MAC protocols design have been proposed to offer multiple functionalities like parallel transmissions without interference. The main idea is to distribute the spatial degrees of freedom (DoFs) between spatial multiplexing, beamforming and spatial nulling to schedule multiple concurrent transmissions simultaneously. The performance evaluations of these MAC protocols based on DTMC models remain unexplored.

In the following section we show how to integrate the MIMO physical layer capabilities into the performance model. Without loss of generality, we consider only the SPACE-MAC [18] for the study to illustrate the new performance model design. The SPACE-MAC protocol is a MAC layer asynchronous protocol design. It combines beamforming with spatial multiplexing and nulling as a multiuser technology. The basic idea is that all transmitter nodes that want to initiate a new transmission and all potential receivers must handle interference to or from already ongoing transmissions. To extend the Bianchi's model to the SPACE-MAC protocol, a new dimension should be added to express the spatial dimension of MIMO communication link. In this regard, two options are available:

- Adding to each state of the Markov chain a new stochastic process,  $\text{DoF}_j(t)$ , representing the used DoFs for a node  $j$  at time  $t$ , where  $\text{DoF}_j(t) \in [1, M]$ , and  $M$  is the  $j$ 's number of antennas;
- Markov chain for each DoF. Figure 11 shows the incremental Bianchi's model.

When a link is active, it can allocate all its DoFs for spatial multiplexing. Therefore,  $M$  data streams can be simultaneously transmitted on that link. Consequently, the normalized per-node throughput for MIMO networks  $S_{MIMO}$  can be scaled at most by a factor of the maximum number of multiplexed data streams ( $M$ ). We obtain

$$S_{MIMO} \leq M \times \frac{P_S P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr} P_S T_S + P_{tr} (1 - P_S) T_C}$$

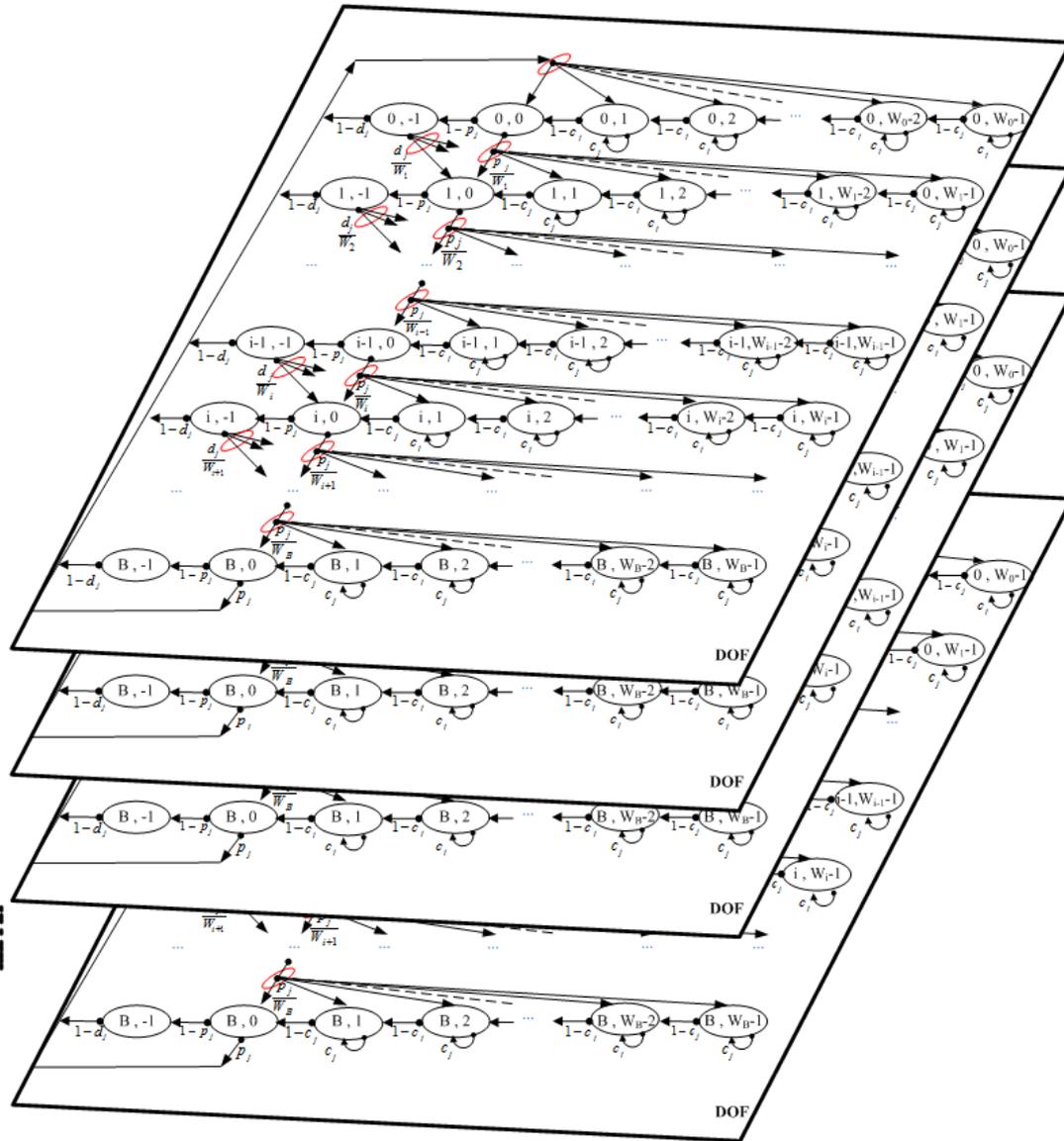


Figure 11. Three-dimensional Markov chain for backoff algorithm (case MIMO)

### 3.2. Performance modeling based on graph coloring and clique constraints

In graph theory, graph coloring is a special case of graph labeling; it is an assignment of labels traditionally called "colors" to the vertices or edges, or both, subject to certain conditions. It has found a number of applications in computer science such as data mining, image segmentation, clustering, image capturing, networking etc. Since a wireless multi-hop network can be modeled as a graph, graph coloring has found its natural place to address some issues related to connectivity, scheduling, resource allocation, frequency

assignment, interference reduction, capacity estimation, etc. In this section we show how to use graph coloring to find a link scheduling policy to satisfy the desired rates. Then, we compute the available link capacity to control the amount of data that could be inserted into the network.

The capacity of any link in wireless multi-hop networks is closely related to the interference relationships between all the active links on the same channel. Conflict graphs offer a way to represent and model such relationships, in which wireless links are represented by nodes, conflicts between links are represented by edges, timeslots are represented by the colors, and allocating time-slots to links can be represented by assigning colors to nodes with no adjacent vertices having the same color. The smallest number of colors needed to color the conflict graph is known as the chromatic number of the graph. If we can color our conflict graph with the fewest number of colors possible, we can schedule all the links having the same color at the same time.

All the mutual conflict links belong to the same complete sub-graph (clique). At each slot time, at most one link in each clique can be active. This rule is converted to a constraint and we will show when this constraint becomes necessary and/or sufficient.

### 3.2.1. Preliminary and definitions

The link capacity in a single-hop network can be defined as the physical transmission bit rate of the source, determined by: the Shannon limit, the fixed modulation scheme and the bit error rate. In a wireless multi-hop network context, several links share the same transmission medium, and so the link capacity decreases when more simultaneous transmissions occur. The sum of all active data stream throughputs in the same interference area gives the consumed capacity. Consequently, the available link capacity is the difference between the link capacity (in a single-hop network) and the consumed capacity:

$$\text{Available Link Capacity} = \text{Link Capacity} - \text{Consumed Capacity}$$

A wireless multi-hop network can be seen at each time instant as an *undirected graph* in which the nodes represent wireless devices, and there is an edge between two nodes if the nodes are within transmission range of each other. The resulting graph  $G$ , called connectivity graph, is undirected because our channel model only considers bidirectional communication links and ignores unidirectional links. Figure 12 shows an example of a connectivity graph. Note that graph  $G$  is not Euclidean due to the radio propagation/interference characteristics.

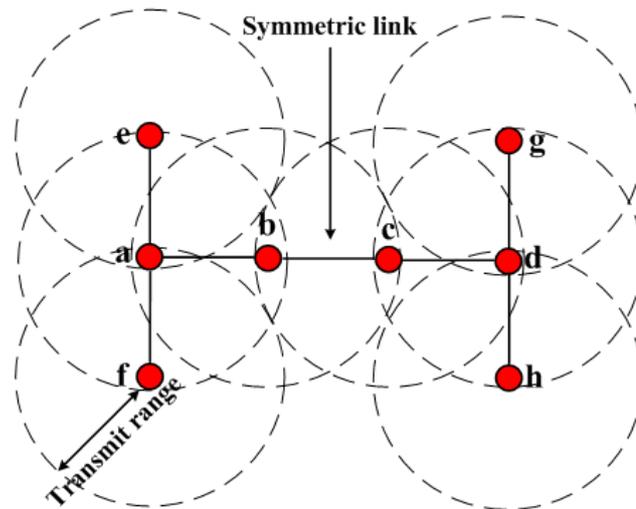


Figure 12. An example of a connectivity graph

We use the conflict graph to model the interference relationships between links and called it the Links Conflict Graph *LCG*. Every link in connectivity graph *G* is represented by a node in conflict graph *LCG*. Two nodes in *G* are connected by an edge if the nodes corresponding to links in *G* cannot have simultaneous transmissions according to the protocol's interference model. For this purpose and as explained in [53], we use the following interference model: **any link within distance *H* from  $(i,j)$  is a potential interfering link**. This rule is called the *distance-*H* interference model*.

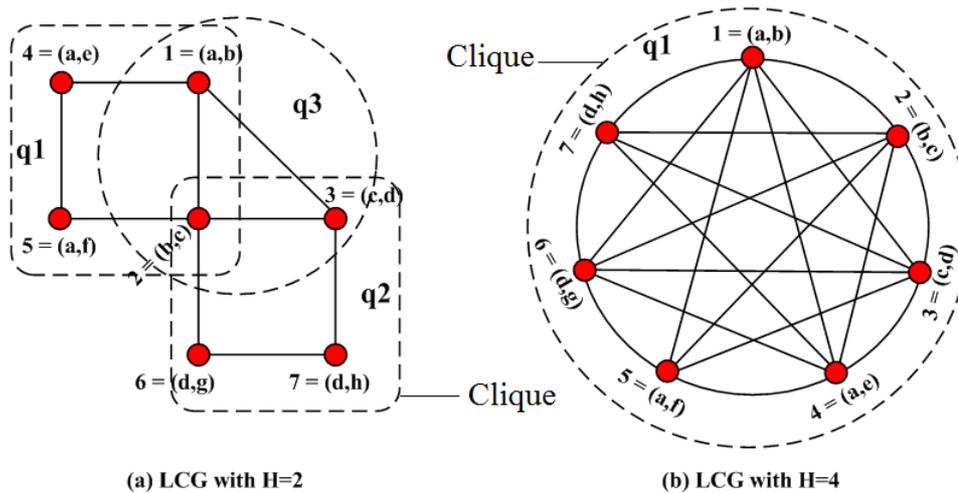


Figure 13. LCGs for network topology

Figures 13.a and 13.b show *distance-2* and *distance-4 LCGs* for the network topology presented in figure 12. In the mathematical area of graph theory, a clique is a complete subgraph. A clique is maximal if it is not contained in another larger clique. In other words, a maximal clique cannot be extended by including one or more adjacent nodes. Determining maximal cliques in the clique graph will allow to determine the set of links

that mutually conflict with each other in the corresponding connectivity graph. The conflict graphs shown in figures 13.a and 13.b have three ( $\{1,2,4,5\}$ ,  $\{1,2,3\}$  and  $\{2,3,6,7\}$ ) and one ( $\{1,2,3,4,5,6,7\}$ ) maximal cliques respectively. We note that, as *distance-H* of the interference model increases, the number of maximal cliques decreases.

Table 1 summarizes the notation used for the link capacity estimation.

Symbol	Definition
$G$	the connectivity graph
$G$ -node	node in the connectivity graph
$G$ -link	link in the connectivity graph
$LCG$	the link conflict graph
$LCG$ -node	node in the link conflict graph
$LCG$ -link	link in the link conflict graph
$C_i$	the capacity of a link $i$ within a SISO single-hop network
$F_i(t)$	the instantaneous flow rate utilization on link $i$ at time $t$
$B$	the scaling factor
$Q_i$	the incidence matrix of link $i$
$\Gamma_i$	the available capacity on link $i$

Table 1. Notation

### 3.2.2. Link capacity estimation with SISO

The  $LCG$ -nodes in a maximal clique represent the maximal set of mutually contending wireless links, along which only one flow may transit at any given time on the channel. Accordingly, the sum of the rates of  $LCG$ -nodes in each maximal clique cannot exceed the capacity of the channel; these conditions define which we call the **clique constraints**. Since the network must satisfy the capacity constraints for all cliques, we can write the clique constraints in a matrix form. We represent a set of flow rates as the column vector  $F$  of size  $n$ , where  $n$  is the number of links in the network  $G$  and  $F_i$  is the average flow rate assigned to link  $i$ . Let  $C_i$  be a column vector of size  $n$  with all entries equal to the channel capacity  $C_i$ . Hence we have,

$$\forall i, Q_i \times F \leq C_i \tag{1}$$

where  $Q_i$  is an incidence matrix, which is of order  $q * n$ . Here,  $q$  is the number of maximal cliques that this link  $i$  belongs to, and  $n$  is the total number of links. The union of the clique matrices across all the links gives the global clique matrix  $Q$ . For example, consider the conflict graph shown in figure 13.a, the corresponding global clique matrix  $Q$  is given by:

$$Q = \begin{matrix} & \overbrace{\begin{matrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{matrix}}^{\text{Links}} \\ \begin{matrix} q_1 \\ q_2 \\ q_3 \end{matrix} & \left( \begin{matrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{matrix} \right) \end{matrix}$$

Note that the flow rate  $F_i$  assigned to link  $i$  in an interval of time  $]t - \tau, t]$ , can be written as:

$$\dot{F}_i = \frac{1}{\tau} \int_{t-\tau}^t F_i(r) dr,$$

where  $F_i(r)$  is the instantaneous flow rate utilization on link  $i$  at time  $r$ . Consequently, equation 1 can be written as

$$\forall i, Q_i \times \dot{F} \leq C_i \tag{2}$$

It is clear that the clique constraints represent a *necessary condition* for a realizable scheduling transmission to exist, since there cannot be a feasible schedule over links that form a violated clique constraint. The challenge is to show that these conditions are also sufficient. Unfortunately, as shown in [53, 54], the sufficiency is acquired only when the conflict graph is:

- A perfect graph, i.e., for every induced subgraph, the clique number equals the chromatic number;
- A unit disk graph, i.e., a planar graph in which an edge exists between two vertices if and only if their Euclidean distance is lower than a constant threshold. In this case, the clique constraints must be scaled by a factor of 0.46.

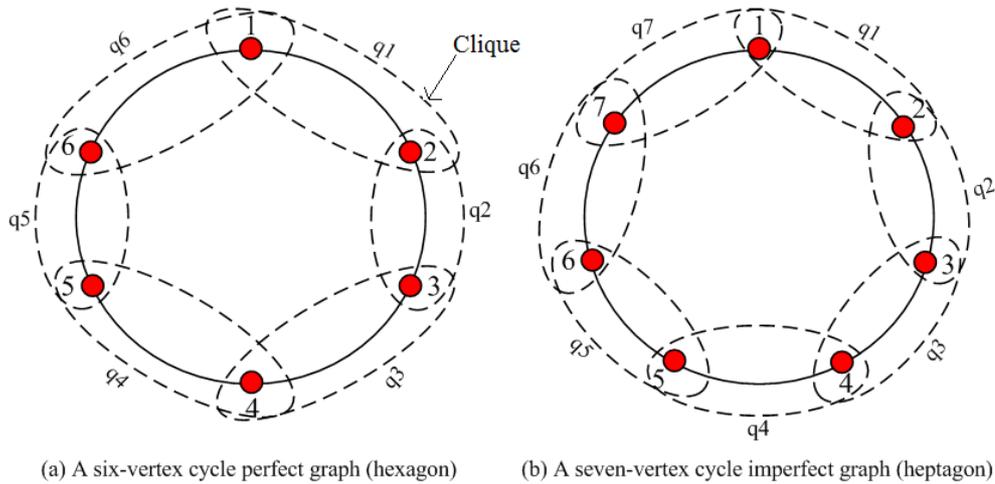


Figure 14. Perfect and imperfect LCGs

Figures 14.a and 14.b illustrate an example of perfect and imperfect graphs respectively. Let the capacity of the shared channel,  $C$ , be 10 time slots. At most 2 *LCG*-nodes may be active simultaneously. Using the clique constraints, the proposed solution for both graphs is 5 time slots for each link ( $0.5C$ ). Figure 15 shows that the proposed solution for perfect graphs (see figure 14.a) is sufficient. However, figure 16.a illustrates the insufficiency of the clique constraints of the imperfect graph shown in figure 14.b. Indeed, a scheduling is

infeasible when each active LCG-node takes 5 time slots. In reality only 4 time slots (0.4C) on each link is achievable (see figure 16.b).

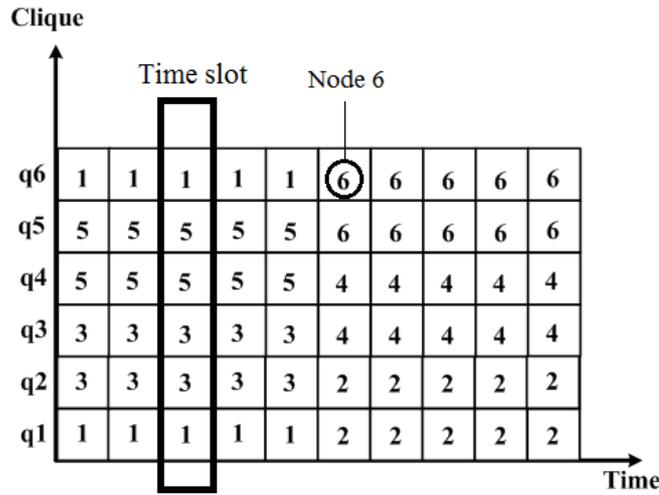


Figure 15. Sufficient conditions based on a perfect graph clique constraints

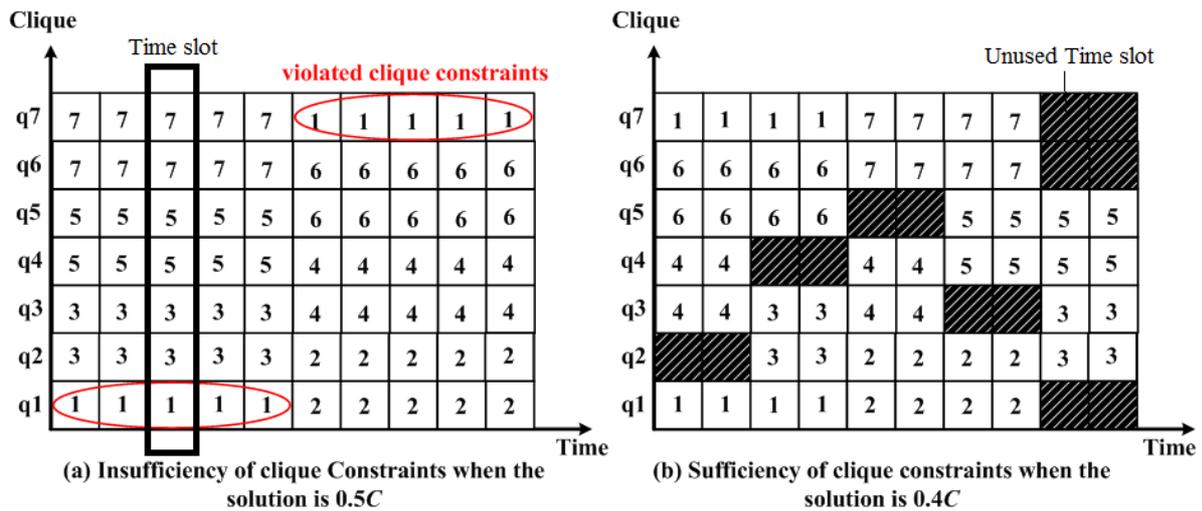


Figure 16. Insufficient conditions based on imperfect graphs clique constraints

In a previous work [53], authors have generalized the notion of scaling factor,  $\beta$ , introduced to the clique constraints independently from the conflict graph type. The value of  $\beta$  is closely related to the used interference model:

- If distance-1 interference model is used, then the average scaling factor value is 0.29;
- If distance-2 interference model is used, then the average scaling factor value is 0.44;

- If distance-3 interference model is used, then the average scaling factor value is 0.71.

In general, and based on the notion of scaling factor, equation 2 becomes:

$$\forall i, Q_i \times \dot{F} \leq \beta \times C_i \tag{3}$$

As the *LCG*-node can be a part of multiple cliques, it considers all the cliques that it belongs to, and takes the worst case available capacity over all the cliques. The available capacity on an *LCG*-node,  $i$ , is

$$\Gamma_i = \min \left\{ (C_i \times \beta) - Q_i \times \dot{F} \right\} \tag{4}$$

where  $\Gamma_i$  is the available capacity on link  $i$ , taking into account active flows on  $i$ , as well as interference from neighboring links. For example, in figure 13.a, let the allocated flow on each *LCG*-node  $\{ 1 = (a,b), 2 = (b,c), 3 = (c,d), 4 = (a,e), 5 = (a,f), 6 = (d,g), 7 = (d,h) \}$  be denoted by  $\{ \dot{F}_1, \dot{F}_2, \dot{F}_3, \dot{F}_4, \dot{F}_5, \dot{F}_6, \dot{F}_7 \}$ . Then, the available capacity on the link between the monitor-forwarding nodes,  $2 = (b,c)$ , is:

$$\Gamma_2 = \min \left\{ (C_2 \times \beta) - (\dot{F}_1 + \dot{F}_2 + \dot{F}_3), (C_2 \times \beta) - (\dot{F}_1 + \dot{F}_2 + \dot{F}_4 + \dot{F}_5), (C_2 \times \beta) - (\dot{F}_2 + \dot{F}_3 + \dot{F}_6 + \dot{F}_7) \right\}$$

In the same way, from figure 13.b we can write  $\Gamma_2$  as:

$$\Gamma_2 = C_2 \times \beta - (\dot{F}_1 + \dot{F}_2 + \dot{F}_3 + \dot{F}_4 + \dot{F}_5 + \dot{F}_6 + \dot{F}_7)$$

### 3.2.3. Link capacity estimation with MIMO

Beamforming and spatial multiplexing techniques allow data streams concentration exclusively on one active link at each time; while spatial nulling allows traffic distribution between different concurrent links. We assume that the number of antennas at each node in the wireless multi-hop network is  $M$ . Let  $M_i$  ( $M_i \leq M$ ) be the DoF of the MIMO  $G$ -link  $i$ . At each time, the total number of DoFs allocated for beamforming, spatial multiplexing and spatial nulling cannot exceed  $M_i$ . Consequently, a  $G$ -link  $i$  can support at most  $M_i$  active data streams. Each DATA stream on the shared channel consumes one DoF. A DoF is defined by a pair of Transmit/Receive filters (precoding and receiving vectors). Two DoFs used simultaneously on the shared channel must be orthogonal to each other or have a low cross-correlation. Destructive interference can occur when two or more concurrent  $G$ -links are simultaneously using non-orthogonal or high cross-correlation DoFs due to:

- imperfect (and possibly very bad) estimation of the channel of active links in the collision area;
- mobility;
- the number of data streams in the collision area exceeds the number of available DoFs.

The first and second reasons can be avoided respectively by perfect channel estimation and static network assumptions. However the third reason can be expressed in the clique constraints.

Denote  $Tx(i)$  and  $Rx(i)$  the transmitter and receiver of  $G$ -link  $i$ , respectively. The average flow rate,  $\dot{F}_i$ , assigned to a  $G$ -link  $i$  is the sum of the multiplexed data streams ( $S_i$ ) among all available DoFs transmitted by  $Tx(i)$  to  $Rx(i)$ :

$$\dot{F}_i = \sum_{j=1}^{M_i} S_i^j$$

The set of all flow rates assigned to each  $G$ -link in the connectivity graph  $G$  is given by

$$\dot{F} = (\dot{F}_1 \quad \dots \quad \dot{F}_i \quad \dots \quad \dot{F}_n)^T = \left( \sum_{j=1}^{M_1} S_1^j \quad \dots \quad \sum_{j=1}^{M_i} S_i^j \quad \dots \quad \sum_{j=1}^{M_n} S_n^j \right)^T$$

Where  $n$  is the number of  $G$ -links in the connectivity graph  $G$ . The available capacity on an  $LCG$ -node,  $i$ , is

$$\Gamma_i = \min \left\{ (M_i \times C_i \times \beta) - Q_i \times \dot{F} \right\}$$

### 3.3. Asymptotic capacity modeling

Asymptotic capacity analysis helps to determine how the achievable throughput of each node and/or the overall network scales as the number of nodes,  $n$ , increases. Such investigation is essential to understand and predict the behavior of large-scale networks. Transition phases from good capacity to poor capacity, or vice versa, may occur when the number of nodes increases. In this case, a threshold determination becomes a necessity.

Usually, upper and lower bounds do not match. When this happens (a gap between the upper and lower bounds), constructive methods try to lower the upper bounds and/or raise the lower bounds until they match. Consequently, algorithms are used to compute one of the bounds (the most simple) and the other is obtained by construction for a maximal matching.

This section investigates the capacity bounds modeling of large random SISO and MIMO wireless multi-hop networks. For the upper bound, critical constraints are applied. Each of them is used to obtain a related bound on the network capacity, and the minimum value between the obtained bounds determines the upper bound. For the lower bound, a constructive scheme is used to match the upper bound. It is based on several steps varying from network partitioning to scheduling and routing. After the model networks have been trained, we describe the critical constraints and the steps of the constructive scheme.

#### 3.3.1. Random wireless multi-hop networks modeling

We assume that  $n$  nodes are randomly located on the surface of sphere of unit area ( $S^2$ ) or torus of unit area ( $T^2$ ). These geometric topologies without borders are used to avoid edge effects, which otherwise complicates the analysis. Each node selects a destination randomly and so a node may be the destination of multiple data streams. Each single data stream can support a fixed data rate of  $W$  bits/sec. The per-node throughput  $\lambda(n)$  bits/sec is defined as the minimum data rate that can be sent from each source to its destination via multi-hop routing. We use slotted time for transmissions. All transmissions employ the same nominal range or power. For the interference model, two models are proposed:

- Protocol model: Let  $X_i$  denote the location of a node  $i$ , and  $r(n)$  the common range. A transmission from node  $i$  to node  $j$  is successful if for any other node  $k$  that is transmitting simultaneously,

$$\begin{cases} |X_i - X_j| \leq r(n) \\ |X_k - X_j| \geq (1 + \Delta) \times r(n) \end{cases}$$

- Physical model: Let  $T$  be a subset of nodes simultaneously transmitting, and  $P$  be the common power level. A transmission from node  $i$  to node  $j$  is successful if

$$\frac{\frac{P}{|X_i - X_j|^\alpha}}{W + \sum_{\substack{k \neq i \\ k \in T}} \frac{P}{|X_k - X_j|^\alpha}} \geq \beta$$

where  $\beta$  is the minimum signal-to-interference ratio (SIR),  $W$  is the ambient noise power level and  $\alpha$  ( $\alpha > 2$ ) is the attenuation factor.

### 3.3.2. Critical constraints and constructive scheme

The upper bound on random wireless multi-hop networks is generally limited by three constraints: 1) connectivity constraint to ensure that the network is connected, so that every source destination pair can successfully communicate, 2) interference constraint to compute the maximum number of simultaneous transmissions on the channel according to the interference model, and 3) destination bottleneck constraint to determine the amount of what can be received by a destination node.

The most common method [55-63] used in literature to determine the lower bounds on the capacity of large-scale random wireless multi-hop networks is based on a constructive scheme. It consists of several steps and uses mathematical modeling.

The first step is called network partitioning. It consists in dividing the unit sphere area into small polygons, called cells. Each cell can be a square, hexagon, regular polygon or irregular polygon as in the Voronoi tessellation. The shape of cells is important to control and capture the spatial node distribution. The size of each small cell should be cleverly designed so that the maximum data rate that can be received by the nodes inside the small cell can be computed exactly. Indeed, if the size of each small cell is set too large, then the maximum number of data streams that can be received by the nodes inside the square cannot be computed exactly. On the other hand, if the size of each cell is set too small, then the maximum number of data streams that can be received by the nodes inside the square is likely to be over-estimated, leading to a loose upper bound.

The second step is called interference management. It consists in bounding the number of interfering neighbors of each cell. This step allows traffic measurement on each cell and interference-free scheduling. Two cells are interfering neighbors if there is a point in one cell which is within the interference distance of some point in the other cells.

The third step is to define the scheduling method to avoid potential interference among active links. Most research work in this area considers the TDMA scheme due to its simplicity. Each cell becomes active, i.e., the nodes in the given cell can transmit successfully to nodes in the cell or in neighboring cells, at regularly

scheduled cell time slots.

The fourth step is to define the routes of a packet on the polygon tessellation. Generally, packets are routed through the cells that lie along the straight line joining the source and the destination node.

The last step is to calculate the expected routes that pass through a cell and infer the expected traffic of each node.

### 3.3.3. Throughput Capacity with SISO

In their seminal paper [55], Gupta and Kumar introduced a fixed random network model to study the throughput capacity of ad hoc networks. The capacity upper bound is determined using the three critical constraints (connectivity, interference and destination bottleneck). The capacity lower bound is determined by the following constructive scheme:

- Define the Voronoi tessellation (see figure 17);

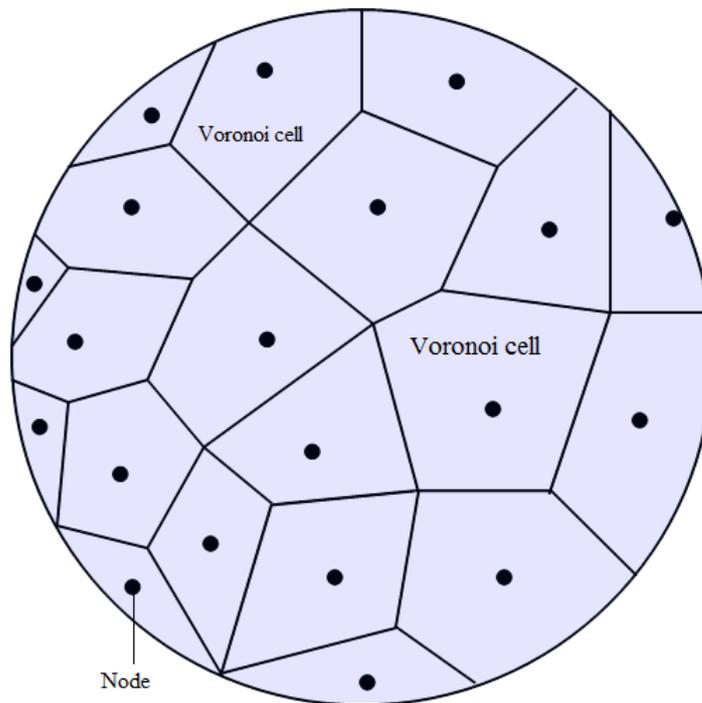


Figure 17. A Voronoi tessellation of  $S^2$

- Bound the number of interfering neighbors of a Voronoi cell. Two cells are interfering neighbors if there is a point in one cell which is within a distance of  $(2+\Delta)r(n)$  from some point in the other cell;
- Bound the length of an all-cell transmission schedule. In the protocol model, there is a schedule for transmitting packets such that in every  $(1+c_1)$  slots, each cell in  $V_n$  gets one slot in which to transmit;
- Define the routes of a packet on the Voronoi tessellation;
- Prove that each cell contains at least one node;
- Bound the mean number of routes that pass through a cell and infer the expected traffic of each node.

Gupta and Kumar have shown two main results:

- Under the Protocol Model, the order of the throughput capacity is

$$\lambda(n) = \Theta\left(\frac{W}{\sqrt{n \log n}}\right) \text{ bit/sec}$$

- Under the Physical Model,

$$\begin{cases} \lambda(n) = \Theta\left(\frac{W}{\sqrt{n \log n}}\right) \text{ bit/sec} & \text{if feasible} \\ \lambda(n) = \Theta\left(\frac{W}{\sqrt{n}}\right) \text{ bit/sec} & \text{otherwise} \end{cases}$$

Considerable attention has been devoted to improve Gupta-Kumar results by adopting the same modeling method. Grossglauser and Tse [57] showed that under mobility constraints (uniform stationary distribution) a constant throughput scaling ( $\Theta(1)$ ) per source-destination pair is feasible. In [62] the authors study the throughput and delay trade-off. They use a unit torus area and square cells instead of a unit sphere area and Voronoi tessellation respectively. Other studies have examined the impact of multiple channels [59], sender-receiver cooperation [56], K-MPRs [63], directional antennas [61], etc.

### 3.3.4. Throughput Capacity with MIMO

To determine the throughput capacity scaling laws for MIMO wireless multi-hop networks, the same modeling method developed for SISO systems can be extended by adding the MIMO physical layer capabilities (see section 2.2.2). Indeed, the amount of traffic in the network increases under the impact of spatial multiplexing and interference cancellation. A transmitter can send multiple independent data streams simultaneously on a link and multiple conflicting links can be cancelled out. Thus, the critical constraints and the corresponding constructive scheme need to be enriched, which is not a simple task. Due to this difficulty, only a few papers [64, 65, 66] in literature analyze the asymptotic capacity lower and upper bounds of MIMO wireless multi-hop networks. In [64], the authors give a first study on how the capacity scales from a source node to a destination node over a sequence of intermediate relay nodes. In [65], Jiang et al. extended the study to random multi-hop networks.

In [65] authors have given an interesting study. To compute the lower bound on capacity of MIMO wireless multi-hop networks, they assume that all degrees of freedom resource at a transmitter node is allocated for spatial multiplexing. This means that the transmitting and receiving end of the conflicting links cannot cancel interference. For the upper bound, both spatial multiplexing and interference cancellation are considered to increase the overall capacity of the network. The main result obtained in [65] is that MIMO systems can have a constant improvement  $M$  on asymptotic capacity compared to the results of Gupta and Kumar:

$$\lambda(n) = \Theta\left(M \times \frac{W}{\sqrt{n \log n}}\right) \text{ bit/sec}$$

where  $M$  is the number of antennas at each node. To validate the obtained results, figure 18 shows the capacity upper bound behavior. The capacity upper bound increases when the number of antennas increases and decreases when the number of nodes increases.

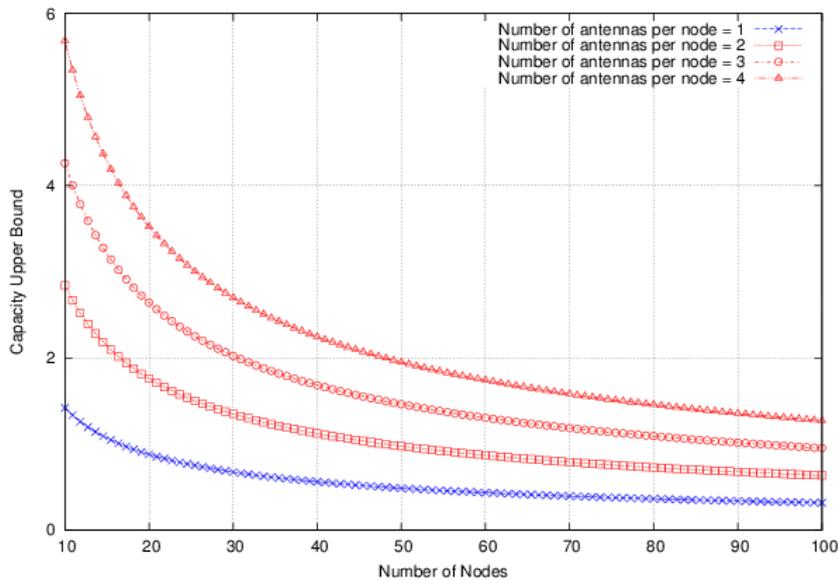


Figure 18. Capacity upper bound of random wireless multi-hop networks

There are still issues that remain unaddressed in capacity scaling laws for MIMO wireless multi-hop. Indeed, the impact of beamforming, spatial diversity, mobility, etc., remains unexplored. Critical constraints and constructive scheme should consider these new constraints.

#### 4. Conclusion

In this chapter, performance models designed for wireless multi-hop networks are considered. We highlight and discuss the different aspects of multi-hop communication, and its introduction in next generation wireless networks. Two physical communication systems are studied: Single-Input Single-Output (SISO) and Multi-Input Multi-Output (MIMO). In order to evaluate the performance of these systems, we have presented three modeling tools: i) stochastic modeling based on Markov-chain, ii) Conflict Graph particularly graph coloring, and cliques, iii) Asymptotic approaches for large-scale networks. Stochastic modeling based on Markov-Chain is mainly used to evaluate the performance of MAC protocol in terms of throughput, and delay. Conflict Graph is used to assess the network capacity in the case of multiple interference domains. Finally, asymptotic study for large-scale networks is presented and discussed in order to assess the upper and lower bands network capacity.

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