Multi-Rate Interference Sensitive and Conflict Aware Multicast in Wireless Ad hoc Networks

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ABSTRACT: *The broadcast nature of wireless medium makes multicast communication subject to various challenges, especially, the unreliability due to the interference [2] and the impact of the transmission data rate choice on the conflicts between communicating users. In fact, a fundamental trade-off exists between communication speed (transmission data rate) and communication range. Actually, the effect of interference is more important when the communication speed decreases, i.e. when communication range increases. In this paper, we propose a multiple rate multicast scheme that is applied to capture the effect of transmission conflicts on the wireless multicast throughput. This work exploits the diversity between users to provide an accurate and efficient method that enables each multicast transmitter, i.e. forwarder or sender, to select the data rates to use to serve its interested neighbours. The choice of the set of data rates, or choice of multi-rate multicast scheme, should be conflict sensitive in order to guarantee high multicast throughput in multi-rate multi-hop MANET's. We start by introducing two new concepts: The transmission data rate based interference graph (TRIGraph) and concurrent multi - rate multicast transmitter set (CMMS). Then, we describe the use of these concepts to characterize the interference conflicts caused by multi-rate multicast transmissions. Unlike all the existing conflict graphs, TRIGraph and CMMS are not only used to model interference conflicts, but they are also used to choose the multicast data rates that reduce the effect of such network inconsistency on the system performance.*

Keywords: Multicast, Multi-rate, Wireless, Conflict graph, Interference, Throughput, Ad-hoc

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1. Introduction

Interference in wireless networks still one of the main inhibitors to wireless performance. It produces a kind of wireless network volatility. That is why; a big weight is given to this issue that remains the subject of a large number of studies. To understand the interference impact and to work out solutions, two wireless interference models are presented: the *protocol model* and *physical model* [1]. A transmission is considered successful under the physical model if the noise power added to the power from all other current transmissions combined at the receiver must be less than a certain SNR (signal to noise ratio) threshold. Let us consider two users x and y. We assume that the communication range and the interference range of the radios at users x and y are the same. If we employ the protocol model of interference, adopted in this work, x transmits successfully a data to y only if (*i*) y is within communication range of x and (*ii*) there is no other transmitting user in the communication range of y, i.e. y is free of interference. In this work, we consider that user y is in the communication range of another user x transmitting at data rate C, if the capacity of the channel between x and y, denoted C_{xy}, verify the relation:

$$C_{x,y} \geq C \quad (1)$$

For bidirectional communications, like communication in IEEE 802.11, we expand the protocol model by requesting an interference free transmitter.

In wireless multi-rate multi-hop networks, since wireless medium has a broadcast nature, routing is subject to various challenges due to many facts, e.g. unreliability of wireless channel due to interference [2] and the impact of the used transmission data rates on the interference conflicts. In fact, direct relationship exists between communication speed (transmission data rate) and communication range. Actually, when communication speed decreases, communication range increases and as a result the interference will has an important effect on the communicating users and on the system throughput. To maximize the multi-rate multicast wireless network throughput, many previous works [6][10] discuss which rate should be chosen by a multicast transmitter (sender or forwarder) in order to serve a set of neighbours (forwarders or receivers). However, these works do not consider the drawbacks of using the chosen data rates on the other communicating users in the network.

Actually, in the literature, the problem of throughput maximisation in wireless networks is reduced to the problem of throughput maximisation of each multicast sub-session (a transmitter and its interested one hop neighbours). In this context, many multi-rate transmission schemes are studied. The worst user transmission scheme [3] specifies that the transmission data rate utilized to serve all concerned users should be the lowest one. The static OMS transmission scheme [3] tries to find the optimal static fraction of users to serve in each transmission in order to maximize the system throughput. The Dynamic OMS [3] adjusts the user selection ratio employed in each transmission based on instantaneous channel conditions. The unicast OMAC splitting based access scheme [4][5] chooses the best channel to serve by applying a sort of splitting algorithm. All The optimisation strategies, previously described, do not consider conflicts between concurrent transmitters. Actually, the concurrent transmissions should be scheduled separately which affects the communication duration and consequently the communication throughput. Many works was introduced to capture the effect of such factors in the context of unicast communication [6] and also in the context of mono-rate broadcast [7], i.e. each transmitter broadcast the data to all its neighbours using the lowest transmission rate possible. In this work, we consider the broadcast advantage in a wireless multi-rate network and we exploit the multi-rate wireless communication feature to reduce the impact of communication conflicts on the multicast throughput.

The rest of this paper is structured as follows. Section II discusses some related works. Section III introduces the system model. The interference sensitive multicast data rate choice method is proposed in Section IV. Section V presents the formulation of the problem and the throughput study of multi-rate interference sensitive multicast. Finally, conclusions and some future works are drawn in Section VI.

2. Related Work

To model the interference impact, two graph types have been introduced in the literature. In the link conflict graph [8][9], as illustrated in Figure 1(b), each link between two nodes in the communication topology is represented by a vertex. If two links may not be active simultaneously, i.e. interfere with each others, an edge should join the corresponding two vertices. Since a wireless transmission may affects multiple links, link-based conflict graph cannot be directly applied to study transmission data rate selection problem. To avoid the resolution of complex link dependencies, a new type of *conflict graph*, the node-conflict graph [6], was designed to facilitate the computation of network throughput. It goes more with the opportunistic nature of wireless communication because it illustrates conflict relationship between transmitter nodes. Each node and all the links to its forwarder in the communication graph corresponds to a vertex in the node conflict graph. Two vertices are joined by an edge if the two corresponding nodes can not transmit at the same time, i.e. simultaneous transmissions may cause the non-usefulness of some links associated with one or both nodes.

In this work, we introduce a new graph, denoted *TRIGraph*, which describes the conflict caused by multi-rate multicast transmissions and consequently helps to choose transmission data rates that maximize the multicast traffic distributed. By the mean of this graph, it is possible to choose the data rates to use for multicast. The chosen transmission data rates should reduce the conflicts while guaranteeing a minimum system performance (in term of throughput).

3. System Model

Let us consider a single source *s* that has to communicate multicast data to a set of receivers R, in a multi-hop wireless network with | N | nodes, $N = |R + F + \{s\}|$. F is the set of forwarders that are not receivers. Receiver nodes can also forward data. Each node n_i ($n_i \in R \cup F$) in the data distribution structure (tree) has a subset of one hop neighbours that are considered as its forwarders $F_i=\{n_{i1}, n_{i2},\dots n_{ik}\}$. $C_i = \{C_{i1}, C_{i2}\dots C_{ik}\}$ is the set of channel capacities of the forwarders such as C_{ij} is the channel capacity of forwarder n_{ij}. Each node n_{ij}, $j \in [1..k]$, within the effective transmission range of n_i, transmits using channel capacity C, can overhear the multicast packet with probability $Pij^{[c]}$(reliability of link (i, j) at data rate C, or packet reception ratio PRR). In order to study the effect of transmission range and interference on system throughput, we assume that $Pij^{[c]}$ of a node n_{ij} is equal to 1 for each multicast data rate $C \geq C_{ij}$ and is equal to 0 otherwise.

We should note that this work is independent of the method of obtaining the channel capacities, that the link reliabilities (in term of packet reception ratio PRR) are known before link scheduling and that the power resources are unconstrained. Also, we consider that the distribution structure was already built (tree graph) and each user knows its next hop neighbours and their corresponding channel capacities. The main task of our contribution is: "*which data rate(s) to choose for multicast in order to avoid conflict effects and to achieve the best throughput possible?*"

4. Multi-rate conflict aware multicast

In this section, we develop a novel and efficient multicast data rate selection scheme that targets to avoid interference effects and to reduce the time wasted to schedule concurrent multicast transmitters. We describe our methodology to compute the all over multicast throughput reached in a wireless network using a specified multicast distribution tree (i.e., given the forwarding candidate set of each node, multicast capacity of each forwarder and node PRR that corresponds to each multicast data rate). The multicast throughput computation should be interference sensitive.

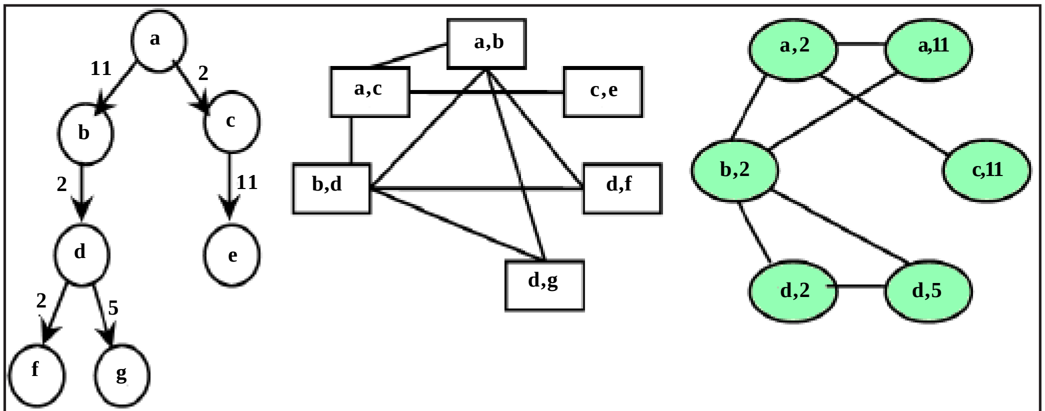
We start by introducing the concept of transmission data rate based interference graph (*TRIGraph*) and concurrent multi-rate multicast transmitter set (*CMMS*). These two concepts are deployed to characterize the conflicts caused by multi-rate multicast transmissions and utilized to choose the multicast rates that reduce the effect of such network inconsistency on the system performance. In fact, as we already described, the transmission range, the link reliabilities and subsequently the set of receivers of a multicast transmission depend on the chosen multicast data rate.

The conflict graphs presented in previous works have been used to represent access constraints in a network. In this paper, we use multi-rate multi-cast conflict graph, *TRIGraph*, not only to schedule wireless transmissions but also to choose the multicast data rate to use in order to reduce conflict effects. The main target of this work is then to choose the optimum multicast data rate of each transmitter. The chosen data rate should help to schedule the multicast transmitters in a way that maximizes the network performance. Next section introduces the concepts of *TRIGraph* and describes the specificity of multi-rate transmission influence on interference conflicts.

4.1 Transmission rate based interference graph (TRIGraph)

In fact, link conflict graph and node conflict graph described previously are deployed in an environment where the transmission data rates used to serve neighbours are already fixed. Each transmitter considers a set of fixed forwarders and their predetermined transmission rates. These graphs only help to schedule transmissions and to reduce interference conflicts. Furthermore, these graphs are made to resolve unicast dissemination conflicts in the context of opportunistic data relaying or multicast dissemination conflicts in the context of mono-rate broadcast. Consequently, they are not suitable for multicast multi-rate wireless networks where the diversity between users is the inherent characteristic.

To consider the conflicts that can be caused by each chosen transmission data rates while computing the throughput of a multicast session, we introduce the new *TRIGraph*. In fact, this new node-rate conflict graph is not only used to schedule transmissions, but it is also used to decide which multicast rates to use in order to maximize the multicast session throughput by avoiding conflicts. By the mean of this graph, we study the conflict relationship between multi-rate multicast transmitters for each available transmission data rate. As shown in Figure 1(c), each vertex in the *TRIGraph* corresponds to a couple (n_i, D^i) where n_i is a multicast transmitter/forwarder in the original connectivity graph and D^i is a transmission data rate that can be used by n_i to serve one or many users (receivers or forwarding candidates from the set F_i). Consequently, the node n_i is coupled with a subset of links, i.e. the links with a capacity higher or equal to the data rate D^i (or links (x, y) such as $P_{xy}^{[D^i]}$). Two vertices (n_x, D^x) and (n_y, D^y) are joined by an edge if n_x and n_y can not transmit concurrently using data rates D^x and D^y, i.e. the simultaneous transmissions causes interference over one or more links associated with n_x, n_y or both. Next section describes how to exploit the *TRIGraph* to localize multi-rate multicast conflicts and how to exploit this information to choose the transmission data rates and to improve the network multicast throughput.



(a) Multicast Tree Graph (b) Link Conflict Graph (c) TRIGraph

Figure 1. The new multi-rate conflict graph : TRIGraph

4.2 Concurrent multi-rate multicast transmitter set (CMMS)

We present the concept of *Concurrent Multi-rate Multicast transmitter Set* (*CMMS*) to capture the influence of multi-rate multicast interference conflicts on the wireless system throughput. This new type of conflict graph is the basis of the choice of the data rate to use for each multicast transmission and is employed to work out the end-to-end system throughput.

We define a *CMMS* as a set of couples (n_i, D^i), n_i is a multicast transmitter and D^i is the data rate such as $D^i \in C_i$. In a CMMS, when all the transmitters n_i multicast simultaneously using their corresponding data rates D^i, all links associated with them (links (i, k) such

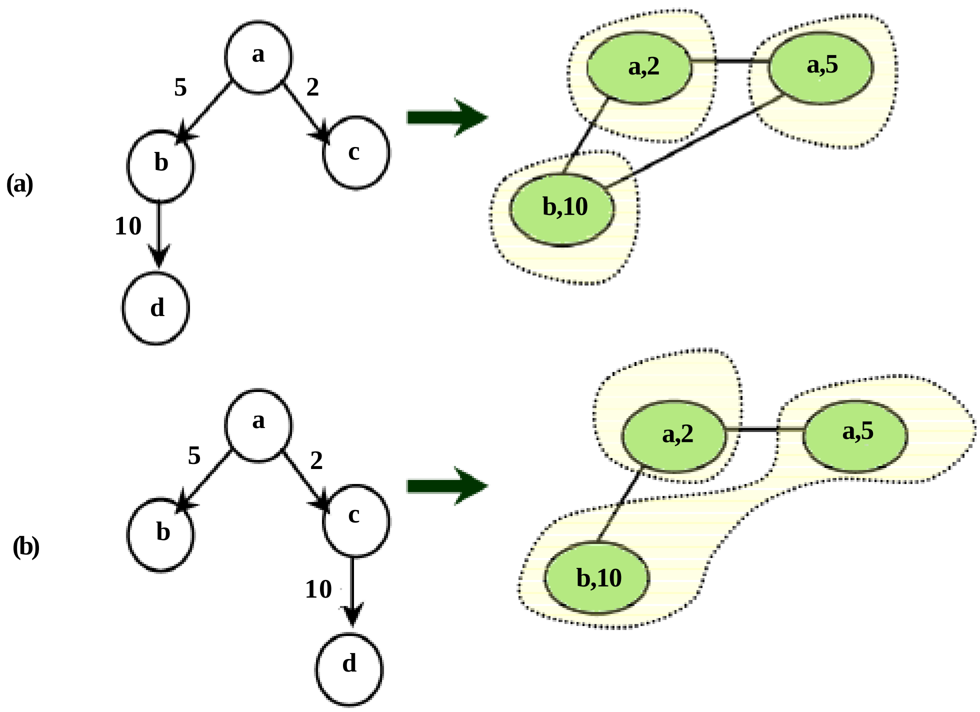


Figure 1.The CMMS *limit* corresponding to each communication graph

us $C_{ik} \in C_i$ and $C_{ik} \geq D^i$) remains interference-free. The *CMMS limit* is a *CMMS* in which we can not add any more couples (adding one more couple produces a non-*CMMS*). Let us consider the *TRIGraph* corresponding to each communication graph in Figure 2.

In the *TRIGraph* of the example Figure 2(a), we notice the existence of three *CMMS*'s, each containing one node. At most one of these sets can be active at any given time. The *TRIGraph* in Figure 2(a) is a complete graph, or a clique. Each set in the *TRIGraph* corresponds to a set of nodes, consequently a set of links. These nodes can be scheduled to transmit concurrently using their corresponding data rates. In the *TRIGraph* of the example Figure 2(b) exists two *CMMS*'s, the first contains only one vertex (node a is associated with two links (*a*,*b*) and (*a*,*c*) if the transmission occurs using data rate 2Mb/s) and the second includes two vertices (node a is associated with one link (*a*,*b*) when transmitting with data rate 5Mb/s and node c is coupled with one link (*c*,*d*) when transmitting with data rate 10Mb/s).

5. Throughput study of multi-rate interference sensitive multicast

The basic issue we want to address is multicast throughput maximization. In this section, we start by presenting the problem formulation then we illustrate the efficiency of our conflict aware multicast method.

5.1 Problem formulation

In a particular dissemination tree, we consider that all the *CMMS* limit are found. At any time, at most one CMMS from the set of all the *CMMS*'s $M = \{\beta_1, \beta_2 \ldots \beta_n\}$ can transmit. If β_i is the scheduled *CMMS*, all the nodes in that set can transmit concurrently. Over a communication period ϕ, ε_i is the time fraction assigned to the *CMMS* β_i, $i \in [1..n]$. As we can deduce, we are in front of a scheduling problem that aims to maximise the end-to-end multicast throughput of the network as described previously and that can be formulated as presented in Figure 3 given some constraints. We denote u_i the size of the set of users $\{ y = y \in F_{n_j}, C_{n,y} \in D^j, D^j \in C_{n_i}\}$, i.e. the number of non served users that can decrypt the data sent by n_i at data rate D^i. The multicast throughput of the *CMMS* β_i during a communication period, denoted $TH(\beta_i)$, is given by:

$$TH(\beta_i) = \sum_{(n_j, D^j) \in \beta_i} D^j \times u_j, \quad \forall \beta_i \in M \tag{2}$$

Consequently, the multicast throughput of the wireless network during the communication period, denoted *TH*, is:

$$TH = \sum_{\beta_i \in M} \varepsilon_i \times TH(\beta_i) \tag{3}$$

The throughput of a multicast session handled by a user $n_i \in N$ is given by the following expression:

$$TH^{n_i} = \sum_{\beta_j \ni (n_i, D^j),\ \beta_j \in M} \varepsilon_j \times D^i \times u_i, \quad \forall n_i \in F \cup R \tag{4}$$

The problem of transmission rate choice, subject to the transmission conflict constraints, so as to maximize multicast throughput can be expressed using the formulation in (5).

$$\begin{aligned}
&\max TH \\
&s.t. \\
&\sum_{\beta_i \in M} \varepsilon_i \leq 1 \\
&\varepsilon_i \geq 0 \quad \forall \beta_i \in M \\
&\varepsilon_i = \frac{\delta_j}{\delta_i} \varepsilon_j, \delta_m \{D^k : (n_k, D^k) \in \beta_m, \beta_m \in M\} \\
&\frac{TH^{nj}}{TH(\beta_i)} \leq 1, \forall (n_j, D^j) \in \beta_i \\
&TH^{nj} = 0, \forall n_j \in R \wedge n_j \notin F
\end{aligned} \tag{5}$$

Next, we illustrate the efficiency of our formulation and we prove that it helps each transmitter to choose the transmission data rates that reduce the effect of multicast interference. By the mean of this formulation, the multicast throughput of the wireless communication system is improved. To validate our work, we compare the results given by our maximization method with the maximum throughput derived from the method that tends to maximize the multicast session throughput and the one that uses the minimum data rate offered to multicast data to its interested neighboring nodes.

5.2 The efficiency of conflict-aware multicas

In the network composed of 4 users shown in Figure 2, we assume that each node can transmit to each neighbor using a specific data rate. For example, in the example Figure 2(a), data rates are C_{ab}=5, C_{ac}=2 and C_{bd}=10. Link reliabilities are: $P_{ab}^{[2]} = 1$, $P_{ab}^{[5]}=1$, $P_{ac}^{[2]} = 1$, $P_{ac}^{[5]} = 0$ and $P_{bd}^{[10]} = 1$. Users b and c are forwarders of user a. A node y can overhear a data multicasted by x with the data rate C only if $C_{xy} \geq C$, i.e. Node y is in the carrier sensing range of node x. For instance, user a can transmit (i) using data rate 2Mb/s, users b and c are covered and can receive the data properly, or (ii) using data rate 5Mb/s, in such case only user b can decrypt the data. Our target is to maximize the data traffic delivered over a communication period ϕ by finding, for each transmitter, the most opportune transmission scheme (or data rates used for multicast) that avoids communication conflicts and reduces their negative impact on the network throughput. For the purpose, the *TRIGraph* that corresponds to each communication tree in Figure 2 is constructed. Each vertex corresponds to a couple (transmitting node, transmission data rate) in the original connectivity graph. An edge joins two vertices if the two related users conflict with each other when using their coupled data rates. A conflict is deduced based on the protocol model of interference.

In the example of the Figure 2(a), as we notice, there are three CMMS's each enclose one couple user/data rate in the *TRIGraph*. The CMMS sets are $\beta_1=\{(a, 2)\}$, $\beta_2=\{(a, 5)\}$ and $\beta_3=\{(b, 10)\}$. Thus, any two users cannot transmit concurrently using their coupled data rates. It is possible to find the most advantageous combination of data rates that maximize the throughput by running the formulation presented in Figure 3. By the mean of this formulation, we perform a deep study of the influence of the multicast data rates used by user a on the system throughput. Two cases are considered:

***Case* 1(*a*)**: If user a transmits with data rate 2Mb/s, only CMMS's β_1 and β_3 are considered. We get an optimal schedule that assigns to β_1 and β_3 the time fractions ε_1=5/6 and ε_3=1/6. The multicast throughput over the multicast period ϕ is then:

$$TH = \frac{\frac{5}{6} \times 2 \times \phi + \frac{1}{6} \times 10 \times \phi}{\phi}$$

***Case* 2(*a*)**: If user a transmits with two data rates 5Mb/s and 2Mb/s, CMMS's β_1, β_2 and β_3 are considered. The optimal schedule assigns to β_1, β_2 and β_3 the time fractions ε_1=5/8, ε_2=1/4, and ε_3=1/8. The throughput over all the multicast communication period ϕ is then:

$$TH = \frac{\frac{1}{4} \times 5 \times \phi + \frac{5}{8} \times 2 \times \phi + \frac{1}{4} \times 10 \times \phi}{\phi} = 3.75$$

In another side, the example of the Figure 2(b) produces two CMMS's. The first CMMS enclose one vertex (couple user/data rate) in the TRIGraph, $\beta_1=\{(a, 2)\}$, and the second CMMS is $\beta_2=\{(a, 5), (c,10)\}$. Thus, users a and c can transmit simultaneously using respective data rates 5 and 10. To find the most advantageous schedule on transmission data rates, the formulations presented in Figure 3 was run for the two cases described as follows. It was found that:

***Case* 1(*b*)**: If user a transmits with data rate 2Mb/s, *CMMS*'s β_1 and β_2 are considered. We get an optimal schedule that assigns to β_1 and β_2 the time fractions ε_1=5/6 and ε_2=1/6. The system throughput over the multicast period ϕ is then:

$$TH = \frac{\frac{5}{6} \times 2 \times \phi + \frac{1}{6} \times 10 \times \phi}{\phi} = 5$$

***Case* 2(*b*)**: If user a uses the two data rates 5Mb/s and 2Mb/s, *CMMS*'s β_1 and β_2 are also considered. However, the optimal schedule assigns to β_1 and β_2 the time fractions ε_1=5/7 and ε_2=2/7. The throughput over all the multicast communication period ϕ is then:

$$TH = \frac{\frac{5}{7}\times 2\times \phi + \frac{2}{7}\times 5 + 10\times \phi}{\phi} = 5.71$$

We should notice that, for a particular sender/forwarder, it is necessary to define all the possible transmission schemes (transmission data rates used). After that, for each transmission scheme, to compute the corresponding time fractions assigned to each CMMS. The fraction values only consider the transmission data rates used by the corresponding scheme. Consequently, for each forwarder/ sender, the time fractions are recomputed for each transmission scheme. Then, the transmission scheme that maximises the system throughput should be chosen.

The session throughput if user a transmits to users b and c with 2Mb/s is $\frac{2\times 2}{1}$ come to 4Mb/s. If user a chooses to serve users b and c using two different data rates 2Mb/s and 5Mb/s, the session throughput is $\frac{2+5}{2}$ equal to 3.5Mb/s. Accordingly , when user a serves users b and c in one transmission using the lowest data, it register better multicast session throughput than the case in which it serves them using two different data rates.

Now, for user a, if we match the cases 1 and 2 in Figure 2(a) previously described to the multicast session throughput information, we find the expected results : over a communication period ϕ, using the transmission data rates 2Mb/s results in a higher throughput than using two transmission rates 2 and 5Mb/s. In this particular case, maximizing multicast session throughput means getting better throughput over a long communication period. In fact, transmitting using data rate 2Mb/s or 2 and 5Mb/s causes conflicts with the other link (b, d) in the communication graph, which means that user c should be paralyzed during all the activity period of user a. Accordingly, as it is given by the proposed formulation, the transmission data rate that should be chosen by a is the one maximizing the network performance, which is 2Mb/s.

In another side, if we compare the cases 1 and 2 in Figure 2(b) previously described to the multicast session throughput information, unexpected results are figured: over a communication period ϕ, using the transmission data rate 2Mb/s results in a lower throughput than using two transmission rates 2 and 5 Mb/s. This is due to the fact that transmitting using data rate 2Mb/ s causes conflicts with the other link (b, d) in the communication graph, but serving user b using 5Mb/s enable links (a,b) and (c,d) to be active concurrently. In view of that, to maximize the multicast session throughput of a does not mean to get higher multicast throughput over the communication period which is mainly due to the conflicts between links.

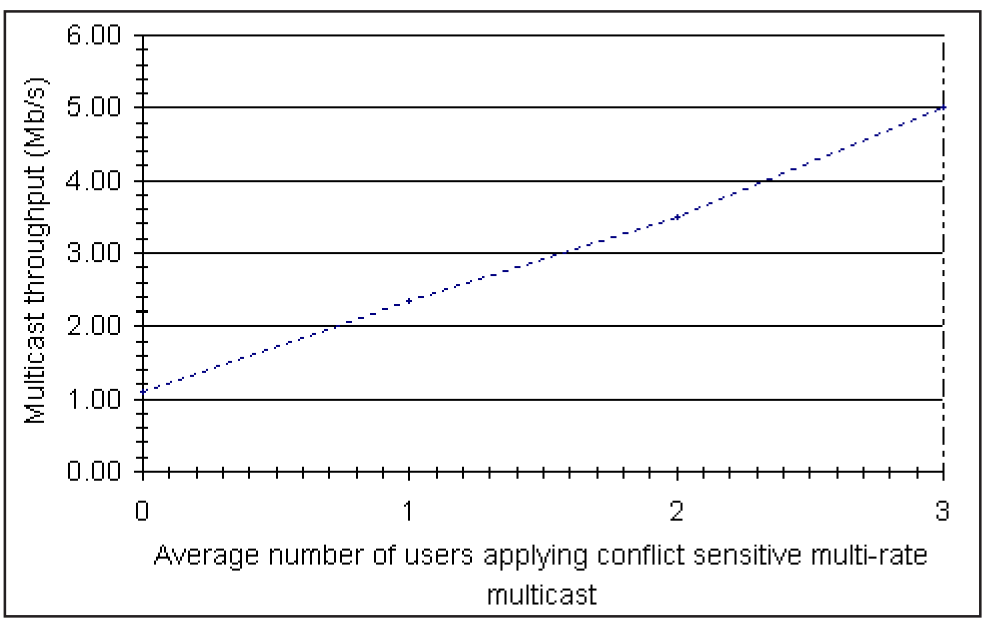


Figure 3. Influence of using conflict sensitive multi-rate multicast on network throughput in a dissemination tree of 10 users

Figure 3 illustrates the influence of interference sensitive multi-rate multicast on the wireless network throughput. In fact, the throughput is improved when the number of users that choose their transmission rate with consideration of the conflict factor is higher. The results are predictable because avoiding conflicts coupled with choosing the highest multicast data rates allow further exploitation of the concurrent transmission opportunities.

6. Conclusion

In the context of multi-rate wireless network,, we studied the impact of the choice of multicast data rates on interference conflicts and consequently on end-to-end multicast throughput in wireless ad-hoc network. We proposed a new transmission conflict graph that considers the offered data rates to model interference. The conflict graph *TRIGraph* and CMMS concepts introduced are not only used to model interference, but they are also used to decide which multicast data rate to use in order to reduce conflicts and to improve the wireless multicast performance. We formulated our throughput maximisation problem subject to the transmission conflict constraints and we proved that the multi-rate multicast scheme enhances the network performance. In the future, it will be appealing to deploy our multi-rate interference sensitive multicast technique to design a routing metric.

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