RBC: Reliable Butterfly Network Construction Algorithm for Network Coding in Wireless Mesh Network

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Abstract— a fundamental problem with network coding in wireless network is to find routes with higher coding and decoding opportunities. Sometimes even if the coding is feasible, the decoding may not be. One solution is to construct a butterfly network within the wireless network. In this paper we develop an algorithm to create a butterfly effect, if it exists, between any single source and single destination chosen randomly in the wireless mesh network. Moreover, our approach allows knowing, at any time, a set of several butterfly networks existing between the chosen source and destination. This reliable algorithm is then pertinent in case of node or link failure and also for performing a load balancing in the wireless mesh network.

Key-Words: - Butterfly Network, Network Coding, Load Balancing, Robustness, Routing, WMN

1 Introduction

Data transmission in wireless networks, especially in wireless mesh networks (WMN), is done via multicast broadcast. All nodes located within the broadcast radius will be able to receive the signal. However, it is impossible for a node to receive simultaneously from two different neighbours. Transmissions must be done in different time periods to avoid collisions.

Some studies[1-3], have been conducted to overcome these problems, and make wireless communication more efficient by allowing simultaneous transmission between nodes even if they are hidden or exposed relative to one another. These studies converge on the use of Network Coding in wireless networks to allow sending simultaneously several symbols from single or several sources.

Established by Ahlswede [4] the Network Coding is an approach for the simultaneous transmission of multiple data streams arriving from one or more sources to one or more destinations without worrying about interference problems.

In traditional networks, the nodes copy and disseminate information. This operation is known as "Copy-and-forward". While in network coding scheme, nodes code received information before broadcasting it. This operation is known as "Copy, and forward code."

Several studies deal with the benefits of the use of network coding in telecommunication networks [1, 3, 5-8]. A Fundamental problem with network coding in wireless network is to find routes with higher coding and decoding opportunities. Sometimes even if the coding is feasible, the decoding may not be. One solution to this issue is to construct a butterfly network within the wireless network. This practice insures to the decoding node to have all required packets relevant to the decoding process. Many papers explore the application of network coding in butterfly networks [1, 9, 10] . However, little research has been conducted to create a butterfly effect in a wireless network [11]. In this paper we develop an algorithm to create a butterfly effect, if it exists, between any single source and single destination chosen randomly in the wireless mesh network. Moreover, our approach allows knowing, at any time, a set of several butterfly networks between the source and the destination chosen. This reliable algorithm is then pertinent in case of node or link failure and also for performing a load balancing in the wireless mesh network.

Figure 1 shows an example of the use of a butterfly effect with a single source and single destination in a mesh network. In this network model the one hop neighbours of the source and the destination are called source's children and destination's children respectively. Also, the two-hop nodes of the source and the destination are called grandchildren. Some nodes belong to the mesh network but they are no member of the butterfly network. The coder node in this model is the source's grandchildren and the decoders one are the destination's children.

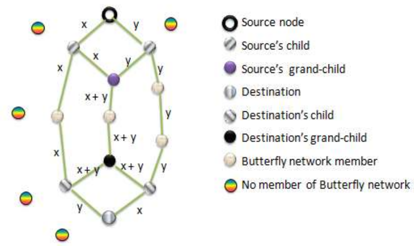

Fig 1. Butterfly Effect in a wireless mesh network

Our solution consists of constructing a butterfly effect between a single source S and a single destination D, based on finding three shortest routes. The first path connects one source's child with one destination's child. The second one connects the other source's child with the second destination's child. Finally, the third path connects one source's grand-child with one destination's grand-child. The three paths have to be disjoint and the grand-children have to be the children of the source's and destination's children. Several disjoined butterfly effects may be created between the same pair (S, D). Simulations are performed in order to show the efficiency of our algorithm.
This article is organized as follows. Section II presents the model of network coding adapted to our work. The section III describes the algorithm used to construct the different butterfly effects in the wireless mesh network. The simulations carried out to validate our approach are presented in section IV. Section V concludes the article. Finally, section VI presents our future works related to this study.

2 Network coding applied to a butterfly network

Figure 1 presents an example of a network coding applied in a butterfly network. The source S sends a set of native packets to destination D. The links can only send h bits per time unit, where

$$h = \min(\text{capacity}\ (l_i)),\ l_i\ \in \text{Butterfly Links} \quad (1)$$

So increasing the throughput can be achieved by applying an exclusive or operation (xor) between packets received at source's grandchildren's node. Set x and y two native packets generated at the source node S, and W the coded packet of x and y. W is coded as follows.

$$W = x \oplus y \quad (2)$$

The coded packet W reaches the destination's children through the network-coded links. Whereafter, the decoding process is executed to extract the native packets x and y. The first destination's child receives the native x packet and the coded one. A simple xor operation between the received data allows the extraction of the native packet y. I the same way the second destination's child can get the native packet x by performing an exclusive or operation between the native packet y and the coded packet. The following formulas demonstrate the decoding operations.

$$x = y \oplus (x \oplus y) \quad (3)$$

$$y = x \oplus (x \oplus y) \quad (4)$$

The destination node D receives than the native packets x and y sent from her children. Note that a redundancy mechanism may be applied on the butterfly network. So each decoder node sends both of the native received packet and the native extracted packet. In this way the destination node get two copy of each native packet.

3 Reliable Butterfly Network Construction

We consider a wireless mesh network, denoted G grouping nodes with a random location for each. The nodes communicate via wireless links. The set of links is denoted by E The set of nodes is denoted by V Two nodes v and u may communicate between them if they are in the same coverage. Therefore, our wireless mesh network will be modeled by a graph G=(V,E) considering, S and D respectively, as the source and the destination during the transmission of data in the network.
In this paper, we develop a solution to build a set of

a butterfly networks between a single source S and a single destination D chosen randomly from nodes belonging to the mesh network G. The use of the butterfly topology is one pertinent solution for insuring the decoding process when the network coding is applied in the wireless mesh network. Our algorithm is reliable since it is able to build many butterflies networks at any time. The backup

ISBN: 978-960-474-316-2

butterfly networks can be used rather when the principal one fails or for performing a load balancing scheme. Note that decoding operation does not need to be carried out at all nodes. Our solution assumes that decoding is performed at the destination's children. This is pertinent if the redundancy scheme is considered during the data transmission. In such case, the destination's children will send both of the decoded packet and the packet

used in the decoding process to the destination D.
RBC algorithm is implemented as follows

STEP 1: Choose S and D, randomly, from $G = (V, E)$.

STEP 2: Find all source children

$$C(S) = \{v \in V, Distance\,(v, S) \leq R\} \qquad (5)$$

Where Distance(v,S) is the distance between the node v and the source S and R is the coverage radius of nodes in G.

STEP 3: For all $u, v \in C(S)$ find the common children of u and v, denoted Cc(u,v).

$$Cc_s(u,v) = C(u) \cap C(v) \qquad (6)$$

Each $w \in Cc_s(u,v)$ has two common parents denoted

$$Pr_s(w) = \{u, v \in C(S)\} \qquad (7)$$

The set of grand-children of S, having each two parents, is denoted GCc(s).

$$GCc(s) = \cup_{u,v \in C(S)} Cc_s(u,v) \qquad (8)$$

STEP 4: Repeat step 1 to 3 for the destination D to get the following equations

$$C(D) = \{v \in V, Distance\,(v, D) \leq R \qquad (9)$$

$$Cc_d(u,v) = C(u) \cap C(v) \qquad (10)$$

$$GCc(D) = \cup_{u,v \in C(D)} Cc_D(u,v) \qquad (11)$$

$$Pr_d(w) = \{u, v \in C(D) \qquad (12)$$

STEP 5: Set $\alpha = 0$, where α is the number of butterfly effects in the wireless mesh network, initialized to 0.

STEP 6: For all nodes $\in GCc(s)$

1. Find the shortest path relaying $w_1 \in GCc(S)$ to $w_2 \in GCc(D)$, denoted e_1 .
2. If e_1 exists, find, e_2,the shortest path relaying $u_1 \in Pr_s(w_1)$ to $u_2 \in Pr_d(w_2)$.
3. If e_1 and e_2 exist, find e_3 the shortest path relaying $v_1 \in Pr_s(w_1)$ to $v_2 \in Pr_d(w_2)$. Where $v_1 \neq u_1$ and $v_2 \neq u_2$
4. if e_i ,$i = \{1,2,3\}$ exist and disjoint, so set $\alpha = \alpha + 1$
5. Construct the α^{th} butterfly network, by relaying
   i. w_1 to u_1 and v_1 , u_1 and $v_1 \in Pr_s(w_1)$
   ii. w_2 to u_2 and v_2 , u_2 and $v_2 \in Pr_d(w_2)$
   iii. S to u_1 and v_1
   iv. D to u_2 and v_2
6. Representation of the α^{th} butterfly network

$$G^{\alpha}_{Bfly} = (V_{Bfly}, E_{Bfly}) \qquad (13)$$

$$V_{Bfly} = \{S, D, w_1, w_2\} \cup Pr_s(w_1) \cup Pr_d(w_2) \cup \{V_1, V_2, V_3\} \qquad (14)$$

$$V_i = \{v, (u,v) \in e_i, i = 1,2,3\} \qquad (15)$$

The butterfly construction algorithm allows finding one or more butterfly network, if it exists, with single source and single destination, in a wireless mesh network. The objective of creating these butterfly networks is to perform a network coding between a source S and a destination D belonging to the wireless mesh network. In fact, we assume that all network nodes are able to perform the network coding, but the decoding does not need to be performed at all nodes but only at destination's children. On other hands, all shortest paths are calculated using Dijkstra algorithm.
Our reliable approach constructs a set of butterfly effects with the same single source anh6d destination (Fig. 2). In fact, this solution is pertinent in the case of links and nodes failures. The existence of several butterfly networks at any time assures the topology recovery scheme. Furthermore, the strength of our scheme appears when applying the load balancing in the mesh network. More than one butterfly effects may collaborate to transmit data by sharing the load within the same wireless mesh network.

ISBN: 978-960-474-316-2

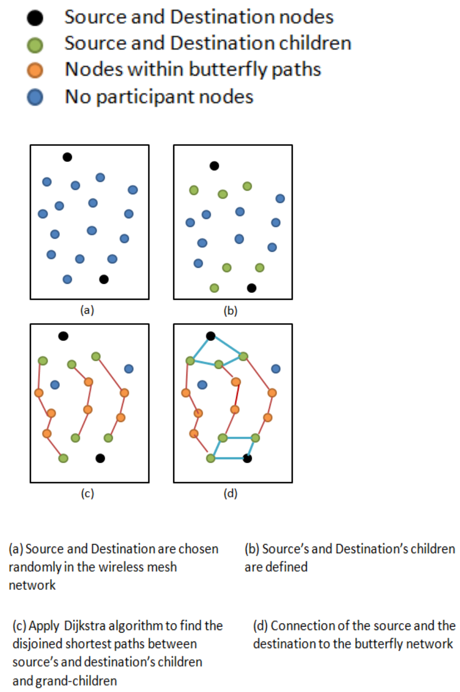

Fig 2. Butterfly construction steps.

4 Simulation

In this section we perform simulation for construction of butterfly networks in the wireless mesh network. We generate 80 nodes in 800m x 800m area. The nodes are randomly deployed with a transmission range of 250 m. We implement the RBC algorithm in Matlab. The objective of the simulation is to construct butterfly effects in a mesh network. Remember that it is more likely to find a butterfly in a mesh network than in a mobile ad hoc wireless network. In fact, in a mesh network, all nodes are more populated. This increases the number of links in a network. Consequently, the number of butterfly candidate links increases also. Note that the source and the destination are chosen randomly from the set of the WMN nodes.

For evaluating RBC algorithm, the simulation has been performed 10 times. Each simulation allows creating one primary and one backup butterfly network. Figure 3 illustrates butterfly networks constructed in two different wireless mesh network topologies, and with two different source and destination couple.

The existence of a butterfly effect requires finding at least three disjoints paths connecting the children and the grand-children of the source and the destination. These paths form the core of the butterfly effect.

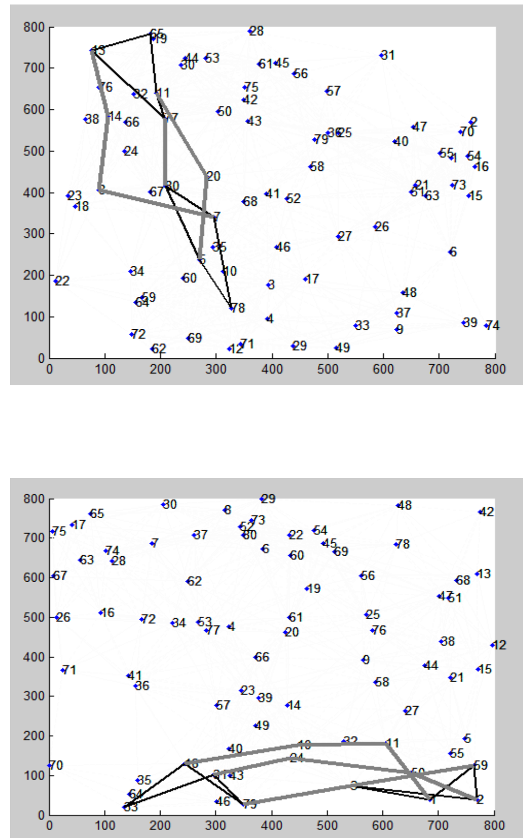

Fig3. Butterfly effects performed with RBC algorithm

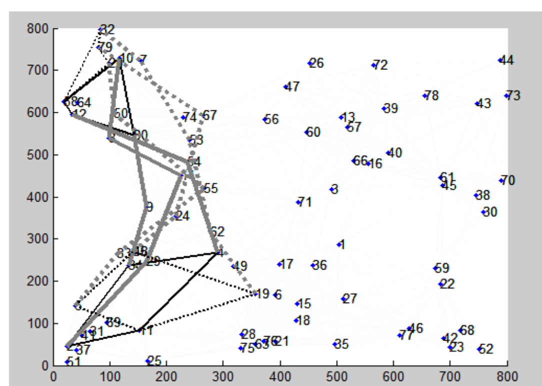

Fig 4 . Primary and Backup Butterfly effects constructed with RBC algorithm

As shown in figures 3 and 4, the RBC algorithm calculates three disjoints paths for each butterfly effect. One path is defined between each pair

ISBN: 978-960-474-316-2

source's and destination's children. One additional path is found between the source's and the destination's grand-children. RBC uses Dijkstra algorithm to find the different shortest path. Furthermore, our results show that RBC is able to find not only three distinct paths to the same butterfly network but also completely disjoint networks butterfly. The purpose is mainly to enable application of the load balancing in the WMN, by using more than one butterfly effect for routing packets from the source to the destination.

As mentioned above, the simulation results show that RBC algorithm allows finding more than one butterfly effect in a WMN. As WMN is more populated with nodes, there is higher probability of finding more butterfly effects. Figure 4 shows a couple of butterfly effects. The first one is called the primary butterfly. It is illustrated with solid lines. The second one is called the backup butterfly, and illustrated with dotted lines. The two butterfly created by our simulation allow the topology recovery without calculating a new routes between the source and the destination. Therefore, our solution is reliable since RBC allows finding a set of backup butterfly effects at any time, to insure the topology recovery in case of butterfly effect fail. The other important result of our simulation is that RBC allows applying the load balancing in WMN in order to increase the throughput. In fact, more than one butterfly effects may collaborate to transmit data by sharing the load within the same WMN.

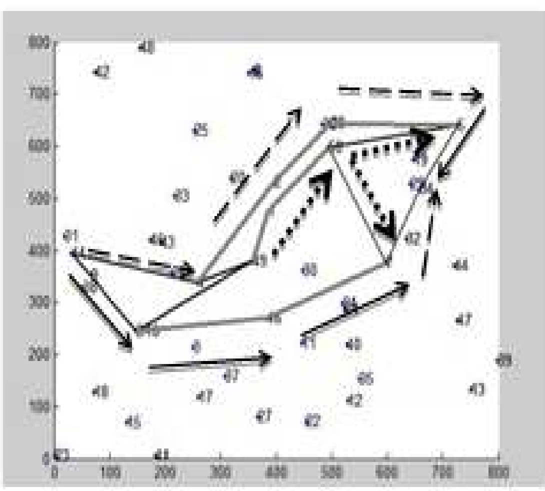

Fig 5. Butterfly based- load balancing in the WMN

The application of the load balancing mechanism is presented in figure 5. The source node uses two paths to transmit the data. The packets sent through the first path, represented by solid arrows, are different from those sent through the second path, illustrated by dashed ones. The coded packets are shown by dotted arrows. The application of the load balancing will than increase the throughput in the network since more than one path are used to transmit data packets.

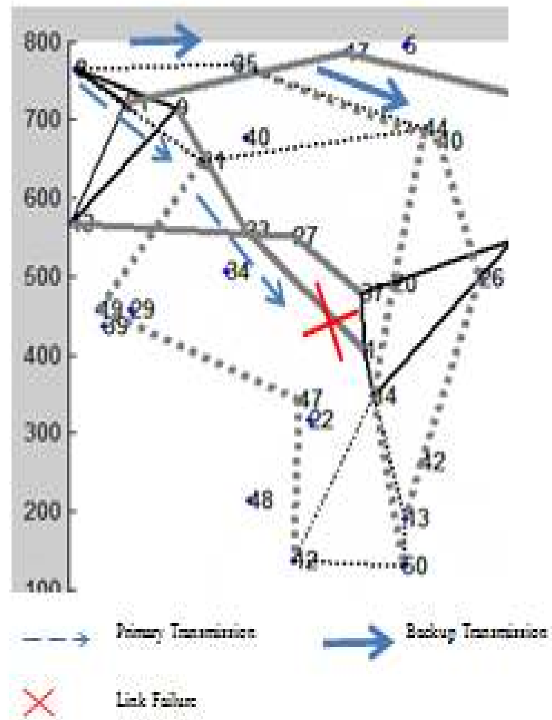

Fig 6 . Backup after Butterfly fail

Figure 6 describes the topology recovery mechanism invoked by a Butterfly fail. The primary butterfly is represented by solid lines and the backup one is illustrated with dotted lines. At first, the transmission is initiated by the source and performed through the primary butterfly network. The packets transmission is shown by the solid arrows. Once one or more butterfly links fail, the source will use the second butterfly network to transmit data. This transmission is represented by the dashed arrows in the figure 6.

5 Conclusion

The use of network coding for improving the performance of telecommunication networks in terms of delay, throughput and packet loss has been

ISBN: 978-960-474-316-2

clearly demonstrated through various studies. But the decoding problem has always been a major issue for achieving objectives of network coding. The network topology has to insure both of the coding and the decoding processes. To meet this need, researches use the butterfly networks for the wired and wireless network.

Although the data transmission in a wireless network is carried out through the diffusion of package, the application of network coding requires the determination of butterfly networks involved in this approach.
However, almost all studies do not address this problem. In this paper, we have proposed a new solution for creating butterfly networks in the wireless mesh network named RBC algorithm. Our algorithm constructs a set of butterfly networks between any single source and any single destination in wireless mesh network. One primary butterfly is used for the data transmission and the others are backup networks. They are used in case of the primary butterfly fails or for performing a load balancing operation. The reliability of our scheme is shown in the availability of the backup butterfly network at all time. Note that the decoding does not need to be performed at all nodes but only at the destination's children. Thus, the redundancy may be applied. In this case both of the decoded packet and the packet used to decoding are sent to the destination.

6 Further works

The results of this study point to many interesting directions for future works. We intend to use this algorithm to develop a new approach for improving the traffic engineering mechanism and redundancy in WMN for several types of traffics, by applying the network coding scheme to increase the throughput and the courteous algorithm [12, 13] for data transmission in order to satisfy both the high priority traffics and the less priority ones.

References:

[1] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard, and J. Crowcroft, "XORs in the air: practical wireless network coding," in *ACM SIGCOMM Computer Communication Review*, 2006, pp. 243-254.

[2] S.-Y. Li, R. W. Yeung, and N. Cai, "Linear network coding," *Information Theory, IEEE Transactions on,* vol. 49, pp. 371-381, 2003.

[3] T. Matsuda, T. Noguchi, and T. Takine, "Survey of network coding and its applications," *IEICE transactions on communications,* vol. 94, pp. 698-717, 2011.

[4] R. Ahlswede, N. Cai, S.-Y. Li, and R. W. Yeung, "Network information flow," *Information Theory, IEEE Transactions on,* vol. 46, pp. 1204-1216, 2000.

[5] C. Fragouli, J. Widmer, and J. L. Boudec, "A network coding approach to energy efficient broadcasting: from theory to practice," in *IEEE Infocom*, 2006, pp. 1-11.

[6] C. Gkantsidis and P. R. Rodriguez, "Network coding for large scale content distribution," in *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, 2005, pp. 2235-2245.

[7] T. Ho, R. Koetter, M. Medard, D. R. Karger, and M. Effros, "The benefits of coding over routing in a randomized setting," 2003.

[8] Z. Li and B. Li, "Network coding in undirected networks," 2004.

[9] S.-Y. Li, Q. T. Sun, and Z. Shao, "Linear network coding: Theory and algorithms," *Proceedings of the IEEE,* vol. 99, pp. 372-387, 2011.

[10] X. Guang and F.-W. Fu, "On random linear network coding for butterfly network," *arXiv preprint arXiv:1001.2077,* 2010.

[11] T. Biermann, A. Schwabe, and H. Karl, "Creating butterflies in the core–a network coding extension for MPLS/RSVP-TE," in *NETWORKING 2009*, ed: Springer, 2009, pp. 883-894.

[12] C. Tata and M. Kadoch, "CAM: Courteous Bandwidth Constraints Allocation Model," in *ICT 2013*, Casablanca, Morocco, 2013.

[13] M. Kadoch and C. Tata, "Courteous algorithm: performance optimization in WiMAX networks," in *Proceedings of the 4th international conference on Communications and information technology*, 2010, pp. 23-32.