The Multi-radio Advantage

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***Abstract*— This paper concerns multi-hop networks with multiple physical interfaces, and more particularly with multiple radios. For these networks, we investigate the advantage provided by the presence of multiple radios and specifically their impact on metrics such as link connectivity and network diameter and their resilience to link failures, and the length of shortest paths. Our results show that "super additivity" properties for the metrics investigated can be achieved by activating the multiple radios available at the nodes. For instance, we show that topologies that with respect to one radio have link connectivity λ_1 and according to the other radio have link connectivity λ_2, when combined into one multi-radio network yield a link connectivity which is $> \lambda_1 + \lambda_2$. Two different topology formation algorithms are investigated for single-radio networks and the advantage of their composition into a multi-radio network is demonstrated via extensive simulations in realistic scenarios.**

***Index Terms*— Multi-radio networks, network connectivity, topology control**

I. INTRODUCTION

The availability of multiple wireless interfaces on a single device, whether it is a computer, a PDA, a cell phone or any among the wide variety of embedded communication systems, is now a widely spread commercial reality. Typical examples are given by the coexistence of Bluetooth and IEEE 802.11 transceivers on laptop and desktop computers, and by the availability of these same technologies plus GSM/CDMA (and even GPS!) in most cellular phone currently on the market. The use of these different technologies is quite differentiated. Bluetooth, for instance, is mostly used for cable-replacement purposes, as in wireless keyboards and mice or headsets; IEEE 802.11 is nowadays *the* way for interconnecting wirelessly to the Internet; GSM or CDMA provide cellular telephony services; etc. A question arise, however, about whether the concurrent deployment of multiple radio interfaces can enhance the performance of network wide protocols, for instance by making routing more robust, or by decreasing the end-to-end data latency.

In this sense, it is relevant to investigate the properties of the network topology obtained by *combining* the different topologies enabled by the multiple wireless technologies. As an example, let us consider and important property such as the *link connectivity* of a given topology G, i.e., the minimum number of links $\lambda(G)$ whose removal from G disconnects it. The higher the λ of a topology G, the higher the selection of routes from source and destination nodes, the better the overall routing. Let us now consider two topologies enabled by two different technologies, such as for instance Bluetooth [1] and ZigBee [2], and let us combine the topologies G_{bt} and G_{rng} enabled by a scatternet formation protocol [3] and by the relative neighborhood graph formation technique [4] over ZigBee, respectively. The resulting topology $G_{bt} \oplus G_{rng}$ is simply obtained by considering the same set of nodes and by enabling each link that is active in both G_{bt} and G_{rng}. What happens of $\lambda(G_{bt} \oplus G_{rng})$? It is easy to see that the minimum number of links to be removed to disconnect $G_{bt} \oplus G_{rng}$ must at least equal the minimum number of links needed to disconnect G_{bt} plus the minimum number of links needed for disconnecting G_{rng}, i.e.,

$$\lambda(G_{bt} \oplus G_{rng}) \geq \lambda(G_{bt}) + \lambda(G_{rng}).$$

In this paper we are interested in investigating when the above inequality holds with the $>$ sign. Furthermore, we want to find out whether similar "super-additive" improvements can be obtained also for metrics as important as link connectivity. In other words, we want to show that deploying *multi-radio* nodes yields the clear *advantage* of enhancing network topology properties that are important for the overall network performance.

We started our investigation in [5], where we considered the model of *random graphs* [6] as the chosen method for topology formation: Given a set of n nodes links are added randomly and independently between each pair of nodes with a given probability p. In that paper our investigation concerned link connectivity, and we show that $\lambda(G_{n,p_1} \oplus G_{n,p_2}) \geq \lambda(G_{n,p_1}) + \lambda(G_{n,p_2}) + c \log n$ holds asymptotically with probability 1 for suitable probabilities p_1 and p_2 and constant $c > 1$. The two main consequences of this result are that the multi-radio advantage (here $c \log n$) tends to infinity as the graphs grow, and also that since the connectivity of the component graphs is $O(\log n)$ for suitable p_1 and p_2 [6] there is a guaranteed constant percentage of *relative advantage*, and this percentage does not vanish as $n \to \infty$.

In this paper we are concerned with the non-asymptotic setting. We consider different topology formation algorithms are in realistic network scenarios that are representative of personal area networks (PANs) as well as wireless sensor networking. In particular, we consider an efficient scatternet formation algorithm for PANs of

Bluetooth devices [3] and a topology formation technique based on the determination of the relative neighborhood graph [4] that is important for the functioning of several geographic based techniques in wireless sensor networks.

Through simulation experiments we consider metrics that go beyond link connectivity. More specifically, we show that given the selected formation techniques, link connectivity is always super-additive. We also show that multi-radio networks are considerably less sensitive to link failure or deactivation that their single-radio components. This property, that we call *network resilience*, shows and even greater multi-radio advantage of that shown by link connectivity. Furthermore, we show that the diameter a multi-radio topology is always smaller than both the diameters of its single-radio topologies, and that is considerably less affected by link removal, in the sense that grows considerably less when links fail of are deactivated. Our last metric concerns shortest path length. We show in this case that a multi-radio topology has paths that are always shorter than the shortest path length in its single-radio components.

The paper is organized as follows. In the next section we briefly describe the topology formation algorithms that we consider for single-radio topologies. In Section III we define the simulation scenarios as well as the metrics of interest and we illustrate the results highlighting the multi-radio advantage. Finally, Section IV concludes the paper.

II. WIRELESS NETWORK TOPOLOGIES

We consider homogeneous networks where a number of wireless nodes are scattered uniformly and randomly in a given plane deploying area. Every node has a transmission radius r, and there is a bidirectional link between any two nodes if they can hear each other transmissions. We call the resulting topology the *visibility topology* of the network, and we indicate by $G = (V, E)$ the corresponding *network topology graph* (Fig. 1(a)). We notice that the network topology graph is different from the *random geometric graphs* as defined by Penrose [7] in that the presence of a link between two nodes does not depend only on their distance being $\leq r$. The topologies we are considering here are those generated from an original visibility topology by applying the following φ functions, i.e., the following formation protocols.

1) **Relative neighborhood graph (φ_{rng}).** If G is a network topology graph, $\varphi_{rng}(G)$ is the planar graph obtained using the *relative neighborhood graph* algorithm presented in [4] (Fig. 1(b)). These graphs have been recently considered for building topology for those networks where geographical routing is to be applied. The planarity of the RNG-generated topology is necessary for implementing face routing, one of the leading techniques for bypassing connectivity holes in both ad hoc and wireless sensor networks and hence guaranteeing delivery even in presence of dead ends [8].
2) **Bluetooth (φ_{bt}).** With $\varphi_{bt}(G)$ we indicate the *scatternet graph* obtained using the Bluetooth scatternet formation algorithm introduced in [3] (Fig. 1(c)). Bluetooth scatternets are considered viable solutions for building networks out of scattered Bluetooth devices and have been widely studied for personal area networking [9].

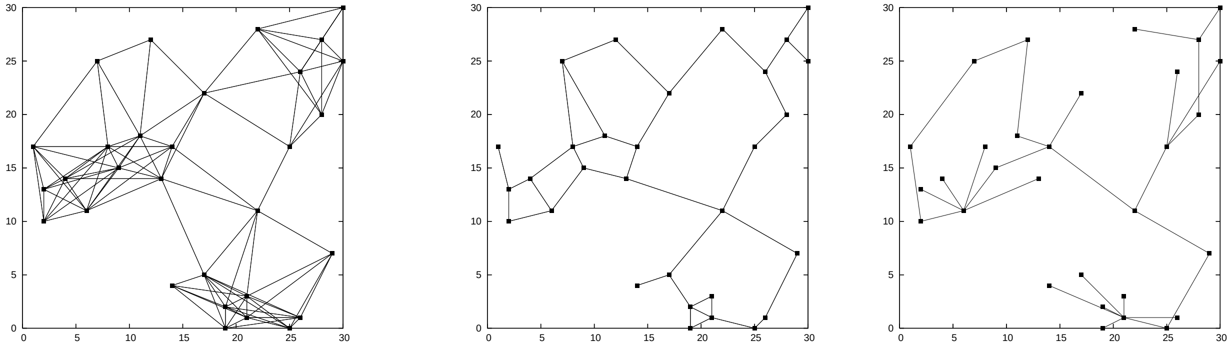
The result of applying φ_{rng} and φ_{bt} to a network topology graph G is shown in Fig. 1.

III. EXPERIMENTAL RESULTS

The topologies formation protocols of Section II have been implemented in a home-grown C++ based simulator. We consider connected networks composed by 30, 50, 70, 90 and 110 nodes randomly and uniformly scattered in a 30m$\times 30$m area. The experiments allow us to assess the multi-radio advantage for the metrics of interest in networks with increasing densities. The transmission range of each node is set to 10m for both the Bluetooth and the ZigBee topologies. All the result values are obtained by averaging over 500 runs for each different scenario. (This guarantees a 95% confidence interval with a 5% precision.)

We are interested in the metrics listed below.

1) **Link connectivity (λ).** The link connectivity of a topology graph G is the minimum number of links whose failure or removal disconnect the network. We have computed the link connectivity by implementing a max-flow algorithm [10].
2) **Network resilience**. The resilience of a topology is defined as the number of links whose removal or failure make the topology graph disconnected. We compute the resilience removing links randomly and uniformly and checking after each removal if the graph is still connected (by using DFS [10]).
3) The **diameter** of a network is defined as the length (in hops) of the longest among the shortest paths between any two nodes. The complexity and performance of many network primitives is proportional to the network diameter. We compute the diameter by running the Floyd–Warshall algorithm for All-Pair Shortest-Paths [10] on the unweighted adjacency matrix of the topology and selecting from the resulting matrix the highest entry.
4) **Diameter sensitivity**. The diameter sensitivity of a topology is defined as the number of links whose deactivation or failure makes the network diameter increase. We compute the diameter sensitivity by removing links from the topology randomly and uniformly. After each removal we check whether the diameter has increased or not.
5) **Shortest path length**. The shortest path length is defined as the average of the minimum distances



(a) A network topology graph G (b) $\varphi_{rng}(G)$ (c) $\varphi_{bt}(G)$

Fig. 1. A network topology graph G and its φ-pruned friends (RNG and BT cases)

(in hops) between all pairs of nodes. The lengths of all the shortest paths are computed by running the Floyd–Warshall algorithm for All-Pair Shortest-Paths [10] on the unweighted adjacency matrix of the topology and by averaging over all the entries of the resulting shortest path matrix.

These metrics are clearly crucial for many functions and properties in networking such as routing and its robustness, broadcast and its complexity, etc.

Link connectivity λ. Fig. 2 show the super-additivity property of the average link connectivity λ. We observe that, independently of the network density 1 ($= \lambda(\varphi_{bt}(G))$) plus 1 ($= \lambda(\varphi_{rng}(G))$) is always > 2! The multi-radio advantage is more evident in denser networks, where the improvement reaches 5%. This is because the minimum network degree of the combined singe-radio topologies is at its maximum in networks with 110 nodes.

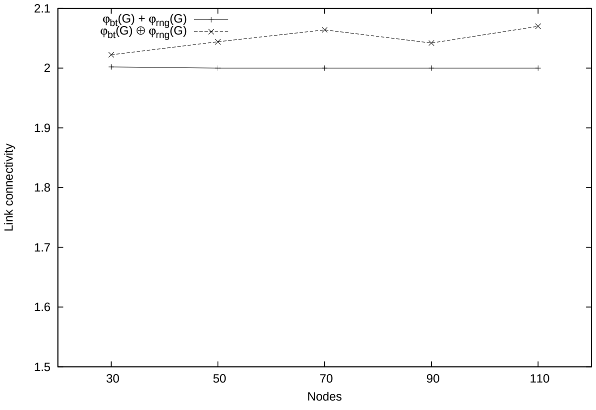


Fig. 2. Link connectivity is always super-additive

Network resilience. Concerning the resilience of a multi-radio topology to random link failures we obtain the results shown in Fig. 3. Similarly to link connectivity, this metric shows super-additive property. In this case, however, the multi-radio advantage, which for link connectivity was kept at bay by the relatively small increase in minimum network degree, explodes because of the randomness of where the faults can occur and increased number of links, especially in dense networks. The improvements of $\oplus$ over "+" go from a minimum of 350% in networks with 30 nodes to 540% in networks with 110.

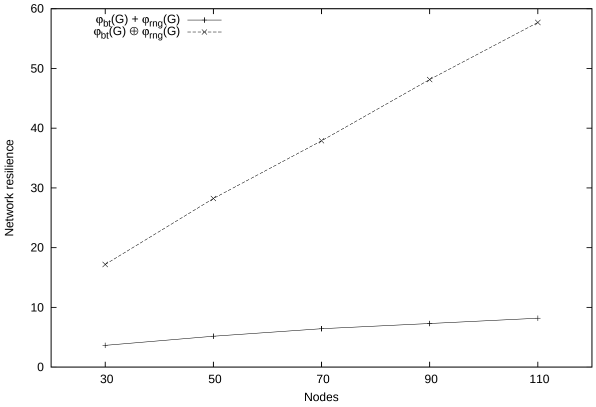


Fig. 3. The network resilience obtained by $\oplus$

Network diameter and diameter sensitivity. Fig. 4 shows that the average network diameter of a multi-radio topology is always smaller than the smallest among the average diameters of the single-radio topologies. The improvement (decrease) goes from 16% for sparse topologies to 18% in dense networks.

We also observe that the average network diameter of a multi-radio network remains the same for a larger number of (random) link failures or deactivations. In other words, diameter in multi-radio networks is less sensitive to link removal than in the single-radio topologies. Results are shown in Fig. 5, where we clearly see that even in a sparse topology, while removing, on average, 3 links is more than enough to increase the diameter of a single-radio topology, we have to remove at least 9 links for the multi-radio diameter to grow.

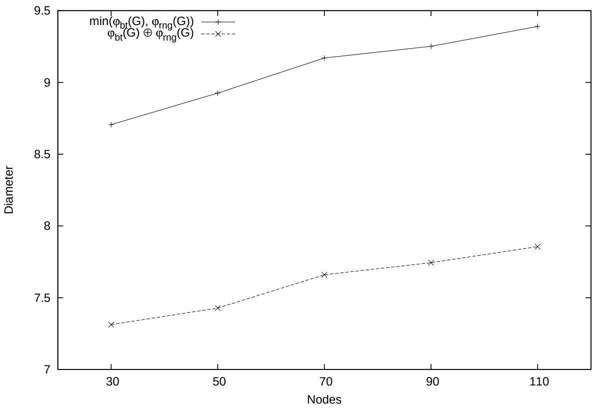


Fig. 4. Decrease in network diameter in multi-radio networks

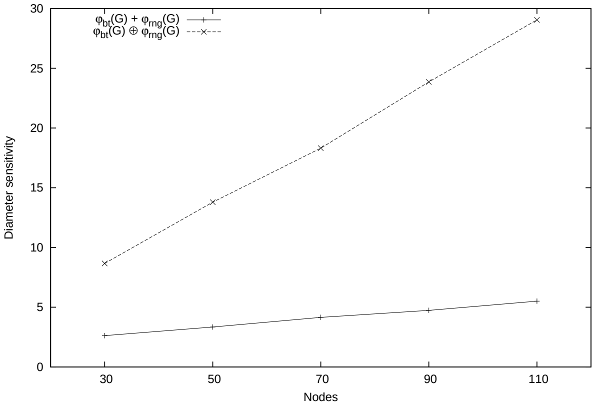


Fig. 5. $\oplus$ makes the diameter less sensitive to link failures

Shortest path length. The average shortest path length on a multi-radio network decreases with respect to the same metric in the single-radio topologies, as depicted in Fig. 6. On average the shortest paths induced by $\oplus$ are 20% shorter than the minimum among the shortest paths of the single-radio topologies that are summed up.

IV. CONCLUSION

In this paper we have investigated multi-hop, multi-radio network topologies as resulting from the natural composition of multiple multi-hop topologies generated by single-radio nodes. For two popular topology formation algorithms, related to current technologies and protocols such as Bluetooth, ZigBee and geographical routing, we have shown that key metrics such as link connectivity and network resilience to link failure exhibit a super-additive property, which demonstrate the clear advantage of using multi-radio. For other metrics such network diameter, its resilience to link failure/deactivation, and for the average shortest path length, we have also shown that multi-radio networks obtain consistent improvements.

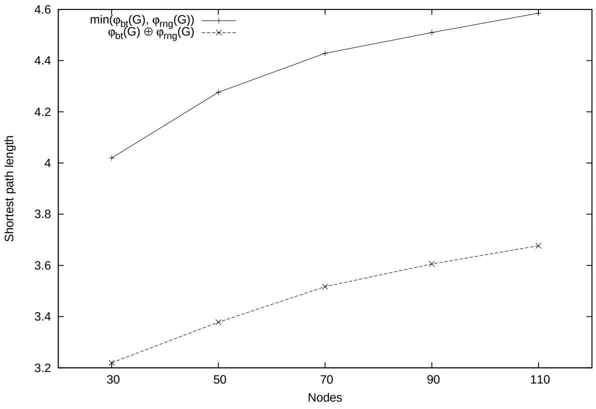


Fig. 6. Shortest paths are shorter in multi-radio networks

This paper offers some initial encouraging results on the much uncharted territory of multi-hop, multi-radio networks. Many other directions need to be further explored, which include further metrics, many more topology formation algorithms, so to possible determine the best formation protocols whose topologies can be combined to yield the best multi-radio advantage.

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