Impact of smart antennas on QoS routing for multi-hop wireless networks

L. Coletti, D. Ciglioni, A. Capone, M. Zambardi

Abstract—**It has been accepted that deploying relays in a cellular network can improve the performance of users near the edge of the cell and has the potential to solve the coverage and capacity problems for high data rates in macro-cells and hot-spot. A number of parameters affects the performance of a multi-hop cellular system including the number of relays, their location and radio resource coordination strategy between users, relays and base-stations as well as routing and forwarding methods.**

The main challenge of designing a routing method for multi-hop wireless network is to consider inherent characteristics of such network and the problem of providing the required QoS to traffic flows. In this hostile network environment relay stations are usually assumed to use omni-directional antennas both in transmission and in reception. Use of omni-directional antennas implies that all transmissions, even unicast ones, are de facto made in physical broadcast.

The introduction of beam forming techniques of smart antennas allows to reduce considerably the use of network resources for every single transmission exploiting angular separation of different paths of flows. This effect is expected to enhance the network throughput.

In this paper the impact of smart antennas on QoS routing for multi-hop wireless networks is presented. System level simulation results show that the implementation of smart antennas could ensure significant gains in term of network throughput. This improvement may compensate the high cost to equip relays with smart antennas.

Index Terms—**Multi-hop, QoS, routing, smart antennas.**

I. Introduction

THE research community has started a huge effort in order to develop a new radio access network able to provide wireless access for a wide range of services and applications across all environments with one single adaptive system for all application scenarios and radio environments [1]. The integration of multi-hop capability into conventional wireless networks is perhaps the most promising architectural upgrade. A new envisioned and promising architecture is the Fixed Relay Network (FRN), where many advantages are expected in terms of coverage, flexibility, throughput and QoS provisioning [2]. A FRN (Figure 1) is constituted by fixed transceivers, called relays, that establish a wireless mesh topology connected through Access Points (APs) to a core network.

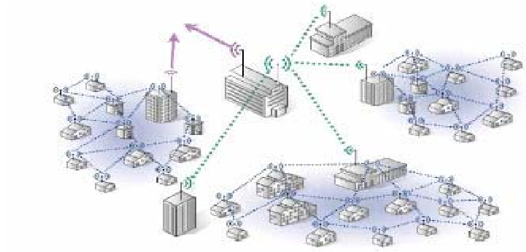

Figure 1: Fixed Relay Network (FRN)

Relays offer connectivity to mobile terminals almost like APs in cellular architectures; for this reason FRNs are also referred to as multi-hop cellular extensions [3]. Even if FRNs are multi-hop wireless networks like MANETs, their characteristics make the routing problem quite different [2]. FRNs have a defined topology and topology changes are mainly due to node failures that are usually not frequent. Therefore, the distribution of network state information is not much costlier than in wired networks, and even a centralized control of route selection can be adopted [3]. Finally, energy consumption is not a problem for network nodes.

In such networks support of multi-hop is mandatory and efficient routing and scheduling algorithms are required to exploit at best network resources and to efficiently manage internal connections and loads from and to the core network. In [4] a QoS routing for multi-hop wireless networks called Wireless Fixed Relay (WiFR) routing has been presented. In that proposal, a new model for the QoS routing problem in multi-hop wireless networks with bandwidth constraints and an algorithm for its solution suitable for Fixed Relay Networks (FRNs) are proposed. The algorithm is based on a heuristic and it is presented with some simulation results. Relay stations were assumed to use omni-directional antennas both in transmission and in reception. Use of omni-directional antennas implies that all transmissions, even unicast ones, are de facto made in physical broadcast, hence, under assumption of homogenous radio interface, transmissions that overlap on

Part of this work has been performed in the framework of the IST project IST-2003-507581 WINNER, partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues, although the views expressed are those of the authors and do not necessarily represent the projects.

Luca Coletti is with Siemens Mobile Communications, via Monfalcone 1, 20092 Cinisello Balsamo - Milano, Italy (e-mail: luca.coletti@siemens.com).

Daniele Ciglioni is with Siemens Mobile Communications, Italy (e-mail: daniele.ciglioni@icn.siemens.it).

Antonio Capone is with the Politecnico di Milano, piazza L. da Vinci 32, 20133 Milano, Italy (e-mail: capone@elet.polimi.it).

Marco Zambardi was with Siemens Mobile Communications, Italy (e-mail: marco.zambardi@icn.siemens.it)

a receiving relay will result in collision and in loss of packets. In other words, when node i transmits to node z (see Figure 2), the radio signal reaches not only node z but also all the other nodes in its radio coverage (u and v) wasting in this way portion of their bandwidth, in fact other nodes don't receive useful signal but anyway they see channel as busy, i.e. they cannot transmit or receive useful signal in the meanwhile.

Moreover in FRN, to compute how much bandwidth is consumed by a transmission, it is necessary to consider not only relays under coverage of the transmitting relay, i.e. relays of its one hop cluster (called neighborhood), but also two-hops-away relays in order to avoid to set up route that will generate collision or overload due to the exposed terminal problem.

The introduction of smart antennas reduces considerably the use of network resources for every single transmission because their "directivity" allows to cover a smaller area and hence to reduce the set of relays affected by a single transmission. This permits to have additional resources to route new connections. In conclusion, the use of smart antennas is expected to enhance the network throughput, that is the number of bytes routed with respect to the number of bytes requested.

The paper is structured as follows. In Section II the mathematical programming model and WiFR algorithm are summarized. Section III is devoted to the selected smart antenna model, while Section IV to the numerical simulation results. Finally, Section V concludes the paper.

II. Wireless Fixed Relay Routing

A model for QoS wireless multi-hop routing problem with bandwidth constraints and the Wireless Fixed Relay routing (WiFR) algorithm for its solution are here summarized [4].

The model is an extension of the well known multi-commodity flow problem [5] where link capacity constraints are replaced with new ones that takes into account interference constraints among different radio links.

Network is represented by a graph with a capacity associated to each link and connections are represented as flows that compete for the limited link capacities; $A(n)$ represents the set of nodes that can be reached from node n and $B(n)$ represents the set of nodes whose transmissions reach n. The objective is to maximize the fraction of offered traffic admitted in the network.

Consider now a set of K pairs of vertexes (s^k,t^k) for k=1,2 …K representing the source and destination node associated with K commodities for which a path shall be found on the graph G. Defining, for each commodities K, the variable F^k as the total units of flow to be sent from s^k to t^k, the objective is to find the optimum α^* which is that particular value of α that satisfies the following function:

$$Max \left\{ \sum_{k=1}^{K} \alpha \cdot F^{k} \right\} \tag{1}$$

where α is a binary variable which states if a single commodity has been admitted completely in the network or refused. Further, conservation equations and non negativity must be satisfied by all flows:

$$\sum_{j \in A(n)} f^{k}_{n,j} - \sum_{j \in B(n)} f^{k}_{j,n} = \begin{cases} \alpha \cdot F^{k} \text{ if } s^{k} = n \\ -\alpha \cdot F^{k} \text{ if } t^{k} = n \\ 0 \quad otherwise \end{cases} \tag{2}$$

$$f^{k}_{i,j} \geq 0 \text{ for all } (i,j) \in E \tag{3}$$

where $f^k_{i,j}$ represents the units of flow of commodity k routed on link from i to j and E includes the set of possible links (i,j).

Differently from wired networks, in wireless multi-hop ones it is not possible to associate a capacity to each link in the graph, since parallel transmissions on different links may be prevented either due to interferences or to the inability of stations to transmit and receive at the same time.

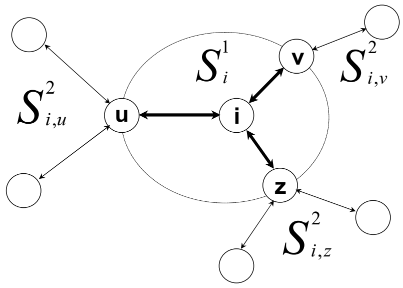

Figure 2: One and two hops constraints of node i

In order to model the capacity and interference constraints, new sets of nodes must be considered: the set $S_i^1=\{(i,j), j \in V\}$, made up by all links that are adjacent to node i, and for each node $j \in A(i)$, the set $S^2_{i,j} = \{(j,k) \mid k \neq i\}$, including all links that have one of their end in j and meanwhile do not belong to S_i^1 (Figure 2). Considering all links within two hops from relay i a new set is expressed as:

$$G_{i} = \left\{ S^{1}_{i} \cup \bigcup_{j \in A(i)} S^{2}_{i,j} \right\} \tag{4}$$

Hence, characterizing each set G_i by a theoretical capacity C_i, representing the maximum aggregate traffic that can be routed on the whole set, the following new constraint (5) must be inserted in the model in order to guarantee the requested bandwidth to each admitted connection.

$$\sum_{k=1}^{K} \sum_{(i,j) \in S^{1}_{i}} f^{k}_{i,j} + \max_{j \in A(n_i)} \left\{ \sum_{k=1}^{K} \sum_{(j,l) \in S^{2}_{i,j}} f^{k}_{j,l} \right\} \leq C_{i} \; \forall G_{i} \tag{5}$$

This non linear constraints can be transposed to a set of linear constraints without any approximation [4].

The model presented guarantees that the rates of routed flows are compatible with radio channel capacity, but does not require to explicitly solve the scheduling problem.

WiFR algorithm [4] assumes that route computation can be performed in a central controller, even if using a proper routing protocol to distribute link usage information, the algorithm could be executed in a distributed way. Since path

selection is performed flow-by-flow, the algorithm can be used for on-line routing of connection requests.
As basis for route searching routine the mechanism of Dijkstra algorithm is used, where the metric is based on weights w_{jk}. Weight of each link is dynamically updated by route computation algorithm taking into account the link residual capacity.
When a route request from relay *s* to relay *t* with a requested bandwidth β (normalized to the provided bandwidth *B*) is delivered to the central entity, this one applies the route searching routine that selects, just among the feasible paths between source node and destination node, the path that has the minor impact on network global saturation level.
In order to examine only feasible paths the following exploring routine determines in a greedy manner if, starting from generic relay *j*, a potential next hop relay *k* should be explored by Dijkstra algorithm or not. The fall-through control steps executed by routine are the following, where *ft(j)* is the free capacity in transmission for relay *j*, *fr(j)* is the free capacity in reception and *ub(j)* the capacity still seen as used by node *j*:

- If *j* is the source node and $ft(j)<\beta$ then connection is refused. In this case source *j* has not enough transmission resources.
- If *j* is the source node, *k* is not the destination node, and $ub(j)+2\beta>1$ connection is refused. In this case source *j* has not enough bandwidth to transmit to *k* and then receive *k* transmission to next node without conflicts.
- If node *k* is the destination node it can be selected.
- If $ft(k)<\beta$ then *k* is discarded. In this case *k* has not enough bandwidth to forward the flow.
- If *i* is a common neighbor of *j* and *k* and $fr(i)<2\beta$ then *k* is discarded. In this case node *i* cannot receive without conflicts the transmissions of *j* and *k*.
- If destination node *t* is a neighbor of *k* and $ub(k)+2\beta<1$ then node *k* is selected, otherwise it is discarded.
- If destination node *t* is not a neighbor of node *k* and $ub(k)+3\beta<1$ then node *k* is selected, otherwise it is discarded.

If the routine states that node *k* can support the new flow then it is explored by Dijkstra algorithm using the metric defined by weights w_{jk}. If the routine instead states that relay *k* is not able to support the new flow no further actions are taken on relay *k*. According to Dijkstra algorithm, these steps are repeated until destination is reached or until no node can be added. If a feasible path ***p*** is found, central controller updates the bandwidth usage information:

$$ub(j)=ub(j)+\beta \quad \forall j \mid j\in p, j\neq t \tag{6}$$

$$ub(k)=ub(k)+\beta \quad \forall k \mid k\in H_1(j), j\in p, j\neq t \tag{7}$$

$$fr(j)=1-ub(j) \quad \forall j\in V \tag{8}$$

$$ft(j)=1-\max\left\{\max_{k\in H_1(j)} ub(k), ub(j)\right\} \tag{9}$$

Equation (6) represents resources consumption of relay forming the new path for transmitting the new flow. Equation (7) represents resource consumption due to the physical broadcast: all neighbors of transmitting relays receive the signal. Equation (8) updates the residual capacity for reception of each relay. Equation (9) updates the residual capacity for transmission of each relay. Also residual capacity values are computed again for each link:

$$rc_{jk}=\min\{ft(j), fr(k)\} \quad \forall (j,k)\in E \tag{10}$$

and weight matrix ***W*** is updated accordingly.
This basic heuristic can be executed online when a new connection request arrives without re-routing already routed flows. In the case the routing algorithm is performed offline on a set of flows, an optimization routine exists that tries to reroute the other flows when no feasible path is found for the considered one.

III. SMART ANTENNA MODEL

In addition to the omnidirectional ones, antennas in general may be classified as directional, phased array, adaptive, and optimal. Their implementation on the relay stations, instead of using omnidirectional antennas, has been taken into consideration. The adaptive and optimal antennas have been rejected because of the high cost to equip relays with these antennas, while the directive antennas have been rejected due to the difficulties to use such antennas in FRNs. In fact the last ones give little flexibility in mesh network scenarios, where it is expected to have fixed (or temporarily fixed) relays with self-configuration and plug-and-play capabilities. This allows an easy and fast deployment of relays that can be done by non experts, e.g. end users, because high configuration efforts are not required.
Therefore our attention has been focused on phased array antennas that don't allow spatial separation of different flows, which can be simultaneously received or transmitted on the same radio channel (SDMA scheme), but permit to select each time the direction where the maximum gain would appear, reducing the number of relays which receive the useless signal.
A phased array antenna uses an array of simple antennas (called elements of the array), and combines the signal induced on these elements to form the array output. Analysing the pattern, it has been recognized that the choice of an array with four elements set up at a distance of $0.5\,\lambda$ and with the same phase guarantees a right compromise between cost, coverage and size of antenna (taking in consideration that spectrum for beyond 3G systems is expected to be well above the 2GHz).

Results of the application of the urban space attenuation model COST 231-Hata [6] in worst conditions and with fixed radio range (i.e. fixed power transmission) on the pattern of such antenna can be represented by the simplified model of coverage shown in Figure 3. It can be recognized that only the main lobe and the first secondary lobes give an important contribution.

The model is suitable for each transmission power because the relations between coverage areas remain unchanged and has the following features:

1) Maximum coverage from -45 to 45 degrees due to the principal lobe (0 degree is the direction of maximum radiation, i.e. the direction toward which we want to transmit). This value has been selected in order to have a safety margin against lobes spreading when the beam is pointed at angles higher than 30 degrees with respect to the normal. In fact in this condition the pattern begins to visibly deform and the lateral lobes increase their width resulting in a higher coverage, thus it's better to have a safety margin.

2) 2/3 of maximum coverage from 45 to 90 degrees and from -90 to -45 degrees due to the secondary lobe. Even if resulting coverage area due to the second lobe is always equal to less than half of maximum coverage, a value of 2/3 has been selected, as said before, in order to work in worst conditions taking into account a safety margin against lobes spreading when the beam is pointed at angles higher then 30 degrees with respect to the normal.

3) No coverage outside these angles because a strong attenuation is expected.

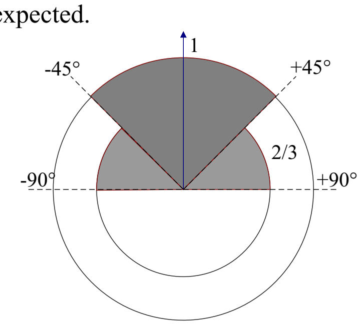

Figure 3: Simplified model of antenna array coverage

The mathematical constraints remain the same proposed before except for (5) which is replaced by the following set of equations, one for each neighbor *z* of node *i*:

$$\sum_{k=1}^{K}\sum_{(i,j)\in S_i^1} f_{i,j}^k + \max_{j\in A_z(n_i)}\left\{\sum_{k=1}^{K}\sum_{(j,l)\in S_{i,j}^2} f_{j,l}^k\right\} \le C_{iz} \qquad (11)$$

$$\forall z \in A(n_i) \quad \forall G_i$$

where $A(n_i)$ still represents all nodes reachable from node *i*, $A_z(n_i)$ represents the set of the only nodes reached by the signal when node *i* transmits toward the neighbor *z*, according to the new coverage model, and C_{iz} refers to the theoretical capacity associated to the subset G_{iz} defined as

$$G_{i_z} = \left\{ S_i^1 \cup \bigcup_{j\in A_z(i)} S_{i,j}^2 \right\} \qquad (12)$$

Using this model of antenna in FRN it is expected to reach a higher throughput because each transmission, keeping on guaranteeing QoS, affects a lower number of relays wasting less network resources; resources that can be used to route new requested connections.

IV. Simulation Results

To evaluate the impact of the antenna model explained above on the WiFR routing [4], a new interference model has been added into the event-driven network simulator ns-2 [7], in addition to the WiFR algorithm and the optimized TDMA MAC layer already developed [4]. The simulations presented here have been conducted using two ray (ground reflection) channel, a provided bandwidth of 2 Mbit/sec, packets of 1Kbyte, given traffic matrix with a number of sources which is the 20% of number of relays and Constant Bit Rate traffic sources with different random data rates which sometimes require up to 30% of provided bandwidth (high traffic). Exponential sources should have been more suitable for FRN purpose but our attention has been focused only on WiFR performance, in terms of network throughput, with or without smart antennas implementation. Different network topologies have been used with different number of relays (30, 60, 90, 120), random distributed over a rectangular area of dimension 1000 m × 1000m. Radio range utilized is from 150 to 550 meters, which is a foreseen region for relay deployment [8]. In addition simulations with omni-directional antennas have been performed using favorable conditions due to the low complexity of such antennas with respect to the smart ones. In fact, given the traffic matrix, routing has been defined trying 30 times to route the given connections selecting them in random order and maintaining the best attempts as final routing. On the other hand, for smart antennas simulation, the order of picking up connections has been given at the beginning and only one attempt has been done.

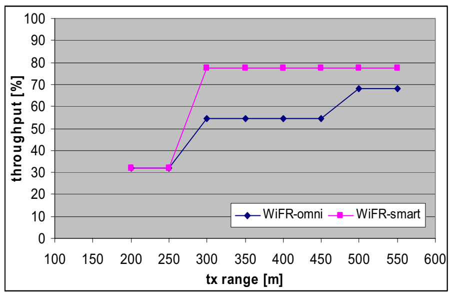

Figure 4: WiFR-omni vs WiFR-smart, 30 relays

It can be recognized in Figure 4 that for 30 relays and lowest values of radio range, the network is partially connected and the number of paths for each couple source-destination is very limited. For this reason blocking effect occurs and algorithm gives the same low throughput in both case. When network reaches low/medium connectivity, throughput obtained equipping relays with smart antennas is increased of about 23% thanks to the lower waste of resources due to the particular coverage of these antennas. As the radio range increases beyond 450 meters, throughput with WiFR-omni increases because of the diminishing of route length and hence of re-transmission, while throughput with smart antennas remains always higher (77%) but constant because the number of connections routed is already so high there is no more bandwidth available.

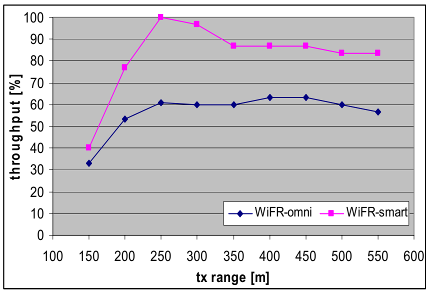

Figure 5: WiFR-omni vs WiFR-smart, 60 relays

Figure 5, obtained with 60 relays, confirms that WiFR-omni is outperformed by WiFR-smart. This gain is already visible at a radio range of 150 meters because the high number of relays allows the network to have high connectivity degree even with lowest value of radio range, exploiting the advantages of smart antennas implementation. In addition, also for these simulations, WiFR-smart curve quickly reaches its maximum value and then keeps itself at value of throughput higher than 30/40% with respect to WiFR-omni one. The only difference with the case with 30 relays is that, reached the maximum (in this case performance of 100 % has been obtained), network throughput starts to decrease, according to the already known WiFR algorithm performances, due to the increased terminal density and the consequent blocking effect [4].

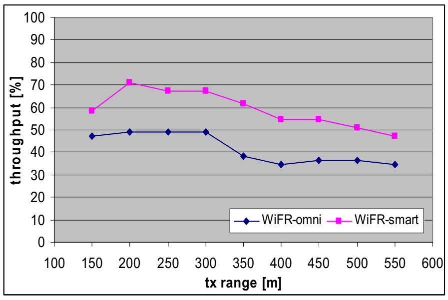

Figure 6: WiFR-omni vs WiFR-smart, 90 relays

Figure 6 and Figure 7 show that WiFR-smart outperforms WiFR-omni even in FRNs with high number of relays (90 and 120).

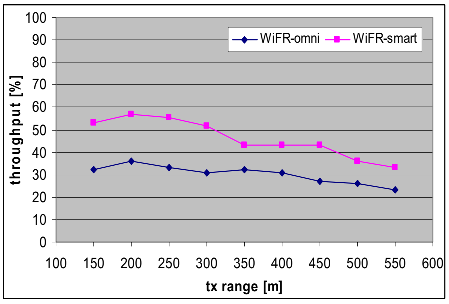

Figure 7: WiFR-omni vs WiFR-smart, 120 relays

It can be noticed that curve obtained with smart antennas follows the profile of curve obtained with omni-directional ones but the gain is only around 10-18%, except for radio range of 150 meters, due to the high number of relays used in these simulations. In fact, as we said, the new model of antenna allows a small number of neighbors to be reached by the useless signal, but the higher the terminal density, the higher the number of neighbors involved which waste their bandwidth, despite of using the new coverage model.

V. Conclusion

From the set of simulations conducted to evaluate the impact of smart antennas on WiFR QoS routing for multi-hop wireless networks, the following conclusions can be taken out.
About random generated topology, WiFR routing in presence of smart antennas outperforms WiFR in presence of omni-directional antennas in network of medium, large dimensions (in terms of number of relays).
The trend of WiFR-smart curves is the same of WiFR-omni ones; in fact it achieves first a local maximum in throughput for a radio range of 200-300 meters, then it starts to decrease (especially in the network with a high number of relays).
WiFR routing with smart antennas has the best gain in networks with a number of relays from 30 to 60. In this range the high cost to equip relays with smart antennas may be compensated by the really high gain in network throughput.
When the number of relays exceeds 60 a significant gain can be still recognized, but the higher terminal density allows that during a transmission the number of relays which receive the useless signal is still high despite of using smart antennas. It results in a lower gain with respect to networks of 30 or 60 relays.
Finally it can be recognized that with the increasing of number of relays a decreasing of transmission range is envisaged in order to have the best performance results. This effect underlines how an efficient power control mechanism that acts as topology control is crucial and suitable for Fixed Relay Networks (FRNs), because it can adapt the terminals transmission power according to network needs [9].

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