Design and Development of a Client Relay System Level Simulator

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Abstract

Growing demand for bandwidth in wireless networks has lead us to almost complete exhaustion of radio frequency resources. In contemporary cellular systems, however, the total capacity could be greatly increased by reducing the cell size. While being attractive, this approach is very expensive and difficult to implement. Client relay is believed to be a promising technique to enhance the performance of cellular networks by allowing cell-edge users to exploit the others as relay nodes. This virtually decreases the cell size and thus improves overall cell capacity.

In this paper, authors present the study of client relay that is believed to be useful for future cellular networks. The operation principle and considerations behind it are explained in detail, an overview of completed and upcoming research is presented. The most interesting results so far are also presented and explained.

Index Terms: cooperative, networking, cellular, wireless, simulation.

I. INTRODUCTION

Commonly used wireless access technologies are about to exhaust the physical layer capabilities. It is possible to implement an OFDM-based digital transmission system with data rates close to Nyquist limit, and leading next-generation cellular technologies, such as IEEE 802.16m [1] and LTE-Advanced [2], are approaching this performance. One of the key obstacles toward effective wireless cellular networking is that multiple cells have to operate in the same frequency band. Whereas these cells are not necessarily adjacent, it is crucial to control the inter-cell interference which otherwise may degrade communication.

As the cells become smaller the dynamic nature of wireless channel makes interference mitigation challenging. The users at the cell edge are typically closer to the neighboring cells that operate on the same frequency. They are forced to use high transmission power to reach their base station. Conventional radio network planning tries to take this issue into account, and if the cells are large enough the problem is solved satisfactorily as shown in Figure 1. White cells use the same frequency, whereas gray cells use another one. Since the path loss of link M_1B_2 is on average higher than that of M_1B_1 or M_2B_2, the scheme succeeds in keeping the path loss between the users of different cells above the path loss to the own BS.

Until recently, network planning schemes controlled the inter-cell interference at tolerable levels. However, driven by the growing demand for bandwidth, operators tend to reduce cell sizes, while keeping the reuse factor as small as possible. Although more bandwidth becomes available to the users, as cell radius r decreases, the path loss $L_{M_1B_2}$ approaches $L_{M_1B_1}$ and $L_{M_2B_2}$ in some spots. Consequently, users M_1 and M_2 increasingly interfere with each other, such that either or both of them are completely unable to communicate with the respective BSs. To some extent, this issue may be mitigated by scheduling the users across all cells to transmit at dedicated times [3] for the cost of extra coordination between the BSs. Resulting in excessive complexity, this approach is also not suitable when cells are not regular hexagons.

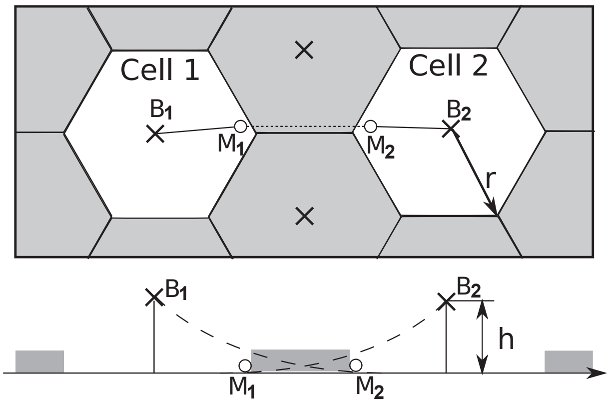

Fig. 1. Cellular network planning with frequency reuse 1:3

The only real solution to the indicated problem without code division is decreasing the required transmission power of the cell-edge users by some sort of relays or distributed antenna systems. For example, static relays may be deployed around the cell to assist remote users. While being effective standard solutions [4], they are expensive to deploy and require much effort to tune properly. Alternatively, the mobile terminals themselves may be allowed to relay packets for each other forming a uniform mesh in coverage area. Various client relay concepts have been studied extensively and in many cases turned out to be prohibitively complex to implement. However, we are quite certain that there exists a compromise solution that seems to be simple and practically feasible [5].

This paper summarizes the evaluation of the client relay and clarifies its motives. It shows step-by-step development of the idea and models built around it. The article is organized in a logical order going from simple system to a more complex one. The first section contains information about the origins of the system under investigation, as well as some core ideas behind. The simplest topology is considered. Second part is devoted to multi-user conditions similar to those in real network. The third part is devoted to challenges related to interference and energy efficiency management. Relay selection is also considered. In conclusion the most important difficulties are highlighted, several new research directions are set based on the encountered scenarios.

II. INITIAL STUDY

It is well-known that shorter mesh-like links result in better data rates [6]. This, however, requires extra signaling to operate properly. This makes it almost unusable for mobile users, because constantly changing channel requires real-time route updates between all nodes. As a result the benefits are negligible compared to instability and unreliability of connection and power expenses in idle mode.

Cellular topology is generally easier to implement, but it requires high transmission powers for the cell-edge users and careful planning to avoid interference. On the other hand, idle node spends virtually no power and requires no signaling to stay online. Also every terminal inside the cell area is guaranteed to receive the service.

One might note, that combining the two approaches might allow for some benefits to be combined. This leads us to a compromise solution, that utilizes cellular-style BS and multi-hop relaying at the same time as in [7]. While BS provides continuous and reliable coverage, relay channels provide extra bandwidth and cover possible shadow areas if needed. This is generally called client relay, and is exactly what we are trying to implement.

The core idea of our implementation is a relaying scheme that does not require excessive signaling like [7]. The scheme we study in its simplest form requires no signaling at all. All the mobiles, however, have to be in the coverage area of the BS.

In our research we use existing 4G cellular protocols as a base line. OFDM physical layer provides a good basis for any sort of relaying, since it compensates for multipath using cyclic prefix. This allows OFDM receiver to combine signals from multiple sources, no matter how many. This means that multiple relays may transmit simultaneously provided they transmit the same data. Therefore, they require no explicit coordination.

By combining the capabilities and topology concerns, a client relay operation principle was chosen. Any node may eavesdrop on the packets sent by other nodes and store them for the subsequent retransmission. Shall one of those transmissions be unsuccessful, a retransmission will be scheduled. Every node that now has a copy of the original packet may now transmit it again, providing multiple sources of the same signal. This results in diversity and power gain at the receiver. After successful transmission packets are dropped from the buffer. Since there may be only one packet en route for a given node, the size of the buffer needed is just one packet per relay session. All signaling used is already present in a typical 4G network protocol. The original sender of the packet does not need to be aware of the cooperative help, so the protocol is backwards-compatible. To avoid excessive transmissions, BS may instruct the original sender not to participate in retransmission at all by means of power control. This operation principle is based on [8] and is described in more detail in [9] and [5].

Let us now assume that there are only 2 client nodes transmitting only uplink packets. The clients are A termed the originator and R termed the cooperator. Both nodes generate new packets that need to be delivered to BS. Additionally, the R may relay packets from the originator. The scheduling information is assumed to be available over a separate channel and is error-free. Cooperative transmissions are carried out by R in the same slot which was granted to A for its retransmission. For example Figure 2, we observe unsuccessful transmissions by node A, while node R performs eavesdropping, and finally a successful cooperative transmission. We notice that eavesdropping is not always useful, since it is impossible to predict if the packet would be captured by the BS at the first attempt.

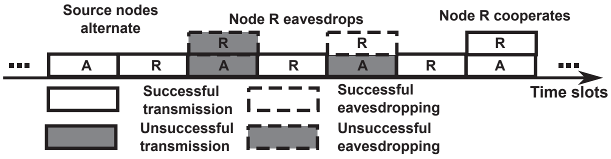

Fig. 2. Client relay example operation

To simplify the model, we assume that each packet is either delivered perfectly or discarded completely. Each node has perfect means of checking the packet for errors and uses decode-and forward principle [10] during relaying. All feedback information is assumed to be error-free, and is available by the end of the time slot. For each combination of sources and receivers there is a well-known constant delivery probability, and the channel is memoryless. The relay channel is assumed to be better then channel without relays according to [11]. This primitive model is the simplest case and can be treated analytically, exact solutions for performance parameters have been found for saturation conditions, as well as stability limits for non-saturated operation. Constructing simulation tool for such system did not present any challenge. Readers are referred to our first publication on the topic [9] for details about this first verion of the simulator.

In the Figure 3 one may find the throughput and access delay gains of the network obtained during simulations for cooperative and non-cooperative cases, compared to those found in [8]. Here we assume that cooperator always cooperates, the channel parameters are matched with the ones from [8]. This results show that although our protocol is simpler and has no inter-node signaling as in [8], it provides the same performance. Although this ”triangle” model is indeed very interesting from mathematical point of view, it is useless in practice. It may be also noted, that if the relay receives the packet with probability 0.4 and the relay channel has 40% better delivery probability then original channel, the average throughput gain for node A exceeds 25% for considered scenario.

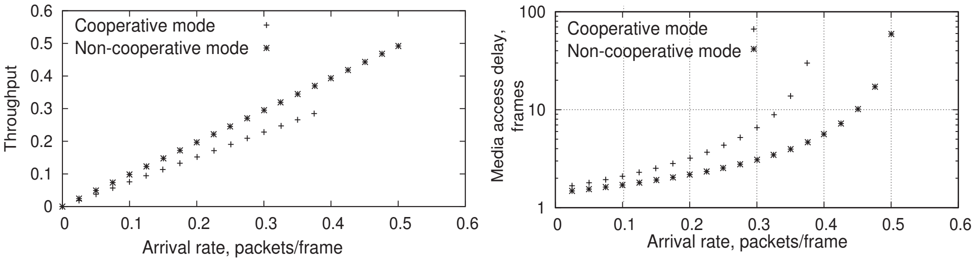

Fig. 3. Simple triangle topology – throughput and delay

III. MULTI-USER ENVIRONMENT

Obviously, a real cell has more than two users. The study of the protocol operation on larger numbers of nodes was done with help of simulation, since it proved to be difficult to obtain any closed-form solutions even for such a simple system. There is still a possibility to find the exact throughput and media access delay in saturation conditions [5]. To allow multi-user scenarios, the simulation tool was improved and optimized to provide acceptable simulation times. Later it proved to be very useful when the model was further extended, since every next extension tends to make simulations slower.

As before, the channels between users are assumed to be static and memoryless. For simulation purposes they are generated randomly with only conditions that channel with extra node transmitting is better then without it for any combination of sources. Although we are unlikely to require every node to join relaying, for such synthetic scenario we allowed that to happen. In fact, for simplicity we have obliged every node to cooperate unconditionally.

Apart from expected capacity increase, the multi-user system has shown some unexpected behavior. For example, with round-robin scheduling of users, the cell throughput was increased. With proportional fair scheduler, however, the throughput gain was much smaller, since the users that could benefit from relays never got scheduled. As one of the results, we have located the dependencies presented in Figure 4. It is interesting that primitive Round-Robin scheduling actually provides very good fairness in client relay network without any throughput penalties when compared to proportional fair.

The contradiction in performance shown above clearly indicates that all parts of resource allocation process should to be reconsidered in order to provide the best solution. This was one of the reasons why the simulation was extended to include realistic resource metrics

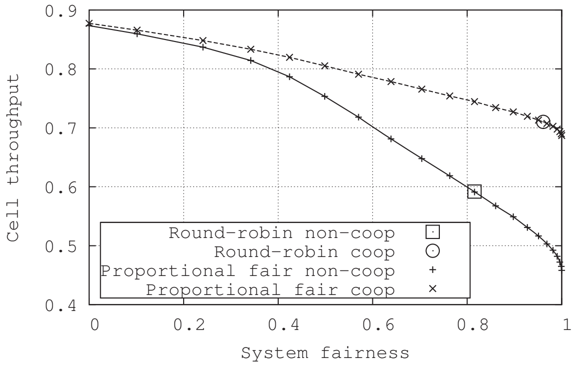

Fig. 4. Scheduler performance under different parameters

like noise levels, channel state updates and so on. It also indicated that the simplified static channel model was not acceptable for such system.

IV. REALISTIC CHANNELS AND DEVICES

Probably the hardest challenge for any wireless technology is the wireless channel. The main concerns in any system are interference between users, the fading effects that make it hard to predict the outcome of a particular transmission, and of course shadowing that creates spots from where mobile terminal can not reach BS at all. Another important concern is power expense, since relaying packets takes extra power from the nodes in the network core. To prove the client relay concept worthy, a simulation tool was upgraded to be capable of multi-cell system-level simulation. It is capable of simulating a cell and its neighbors, as well as providing the performance statistics in terms of energy efficiency, throughput, latency, packet loss and much more. It should be noted that adding real channels to the system that was originally built around static channels has proven to be nearly impossible. In fact, any sort of realistic channels have to be simulated as a separate system that changes over time no matter what happens in the network.

Since the system-level model takes into account many factors, it also needs proper dimensioning. This includes the path loss models, fading models, node parameters, antenna gains, receiver sensitivities, noise figures and many more. The results presented here are based on an urban macrocell scenario from [12]. The node parameters are taken from various datasheets and [13]. Path loss models are taken from [14]for node to node communication and [15] for communication with BS. The transmitter parameters are tuned to match those typical to both LTE and IEEE802.16. The complete list of parameters employed in the simulation would occupy several pages, so interested readers are referred to the documents mentioned above.

Unlike the previous scenario, where we did not care about interference or efficiency, now we need to select relay nodes carefully, so that the interference levels are not increased. The interference generated by the simulated cell is effectively looped back to it, so the more interference is generated the higher are the noise levels. Since each node has to choose the whether to join relaying or not on its own, some heuristics are employed. First of all, nodes will not even listen for packet if their channel is not 2 times better then the one of originator. Secondly, if the packet was captured, it will be relayed with some probability $0 < p_{tx} < 1$. Those two rules only allow a limited amount of useful nodes to become relays. p_{tx} has to be tuned for specific node density.

In Figure 5, we observe the dependence of the cell-average transmission success rates on the cooperation probability $p_t x$. As it increases, the success rate grows. However, at some point extra interference generated by the relays begins to affect the transmissions, and the success rate decays consequently. With our approach, it is possible to locate the 'optimum' that corresponds to the best balance between the generated interference and the relaying gain.

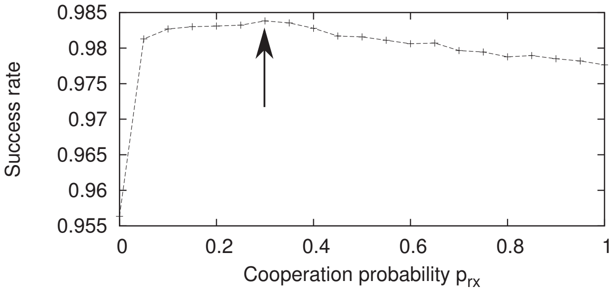

Fig. 5. Average per-node transmission success probability

Although some improvement, namely 8.5% of net cell throughput, can be achieved this way, it is not necessarily the maximum possible gain. It also comes with a price of almost 25% increase in average node's energy expenditure. Selecting the best algorithm for relay nodes is currently the most important issue. In our opinion, this task is important not only in context of client relay, but also in more generic context of cooperative networks. In any cooperative network each node has to decide if it should participate in a particular transmission independently and based on limited information. As the cooperative and ad-hoc networks become ubiquitous, this problem will almost surely require solution.

Currently, we are trying to create a generic cooperation algorithm in hope of finding the best configuration for it by simulating and comparing the performance. Our future work will cover wider range of inputs that could be used for relaying decisions, such as history of channel conditions, new heuristics, data sent from BS and so on. Deeper understanding of physical layer may also provide us with additional options, so this direction is also important in our study.

V. CURRENT RESULTS, FUTURE WORK DIRECTIONS AND CONCLUSION

Our implementaion of client relay concept is still under development. Although it was shown that it is theoretically possible to get really high cell throughput gains of about 20% in a scenario with static channels, it took a lot of effort to get even 8.5% cell throuhput gain in scenario with interference and realistic channels. Unfortunately, so far we have been unable to evaluate a wide range of protocol implementations, since that would require actually implementing all of them.

The next step in our research is dimensioning of the protocol to match some other real technologies, for example LTE-advanced [2] exactly. This will give us better insight into the realistic values of relaying gain for different technologies. Unfortunately, LTE does not yet have a well-defined evaluation methodology established, so for now we are forced to use IEEE 802.16 documentation for references.

Reviewing the obtained results, we think that technologies like client relay will be useful in future networks. Since the bandwidth resources are scarse, some steps need to be taken to improve the cell capacity. At the same time we are not yet ready to abandon macrocellular topology due to high prices on base station equipment and installation costs. Therefore hybrid technologies like client relay may yet play their role in the cellular network evolution and probably become a basis for the next generation of wireless networks.

As a final result, we are hoping to prove that the cellular terminals could cooperate efficiently in wide range of channel conditions without explicit inter-node signaling as, for example, in [16] . The simulation approach would then prove the concept and it probably could be integrated into a real cell for testing. Hopefully, a significant gain in service quality and availability will be provided to the end-users.

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