Stretched Call Model for Next Generation Cellular Networks*

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Abstract—**This paper examines the possibility of implementation of relaying in 3G cellular systems by allowing calls between a Mobile Terminal and Base Station to be forwarded by some other Mobile device in the cell. This "stretched" call provides improvements in throughput, capacity, energy savings and coverage. The main contribution of this paper is to enumerate the problems that are introduced due to relaying, and how they could be resolved. We consider cdma2000, UTRA-FDD and UTRA TDD technologies of 3G cellular, and discuss stretched models suitable for best throughput and delay metrics.**

Keywords—Stretched call, relaying, relay, intermediary, 3G, UMTS, cdma2000, TD-SCDMA

I. INTRODUCTION

Recently, relaying has been investigated as a technique to improve capacity, throughput, coverage and to decrease the transmit power of a Mobile Terminal (MT) in cellular and ad-hoc networks. It was shown by using a single relay the battery life of a MT in a cellular network could be increased by 2-7 times in [1]. Here, relays can either be other MTs, cars or other specialized network elements, using only the 3G infrastructures. Another implementation involves placing, Mobile Relay Stations (MRS) at strategic locations to move the traffic from congested cell to a non-congested cell, to increase the capacity and to decrease call-blocking probability [2]. Here, both cellular and ad-hoc networking technologies are used. Multi-user diversity is used in [3] for delay non-sensitive applications to increase throughput. In [1,2 and 3], the central control is still with the Base Station (BS), and a single relay is used anytime between the MS and the BS. In Opportunity Driven Multiple Access [4] and in Intelligent Relaying [5] techniques, multihop-relaying technique is used using specialized routing algorithms to route the MT packets.

In this paper, we use the terminologies specified in [1]. A relay is called an intermediary, and a relaying connection is called a stretched connection. For a stretched connection, the link between the MT and intermediary is called Lower Arm (LA). The link between the intermediary and BS is called Upper Arm (UA). The connection between mobile and BS is called a Direct Connection. We assume that 3G standards are used for relaying. UMTS supports Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes [4]. Cdma2000 specifications list only FDD mode. The UMTS TDD mode in turn has 2 modes - High Chip Rate (HCR) and TD-SCDMA mode, also called as Low Chip Rate mode.

Relaying in 3G introduces new problems. First, an intermediary's battery power is being used at the expense of another MT. Second, the type of intermediary, and how to choose the best intermediary. Third, since both the MT and the relay can be "mobile", the number of handoff can only increase. Fourth, there is no diversity – dual antennas, smart antennas, Multi-User Diversity (MUD), etc., which the BS provides. Fifth, co-channel interference at the intermediary depends on the transmit power of the neighboring mobiles, which are power controlled by the BS and not the intermediary. Sixth, the security of the data the intermediary is forwarding, has to be ensured. And finally, with the introduction of the intermediary, delay will be introduced. Section II discusses how these problems mentioned in relaying can be resolved. Section III describes the various call models possible by the combination of FDD and TDD modes, by utilizing the propagation environment, mobility of MT and intermediary and the type of traffic. Section IV summarizes the best-stretched models.

II. 3G ISSUES

In this section, we discuss problems introduced by relaying, and how we use our model [1] to solve these problems

A. Type of an intermediary

Relaying requires use of other mobile's battery power, which is a problem. This can be overcome, if we assume that the intermediary has sufficient battery power. Cars for example have ample battery power. In urban areas, cars can be used as intermediaries. Another problem is convincing users to allow their MTs to relay someone else's call! We believe that a differential pricing model (where stretched calls are charged at a higher rate than direct calls) with appropriate credits (either as cash or free call minutes) being provided to intermediary owners will encourage more users to allow their cell phones to be used as intermediaries when "idle". While interesting, in this paper we focus only on the technical problem of implementing stretched calls and leave a discussion of the pricing model to a later paper.

An intermediary can either be in a translating or a non-translating mode [1]. In translating mode, the unit of transmission is a frame, and in non-translating mode the unit of transmission is a Power Control Group (PCG) - a slot in a frame. A translating intermediary is required for the following

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scenarios. First, when the duplex mechanism changes between the UA and LA. Second, when the propagation environment is different in UA and LA, either because one of arms is in LOS and the other is in NLOS, or because there is relatively high mobility in one of the arms.

A side effect of introducing a relay is that the propagation environment for the "selected" stretched connection - both UA and LA can improve over the direct connection. This allows us to use different Processing Gains (PG) for the stretched connection. Increasing the coding rate, decreasing the spreading rate or using higher order modulation can provide better PG. It is also possible that the PGs can differ in LA and UA, in which case, a translating intermediary is required. A non-translating intermediary is used when the physical layer processing is similar for LA and UA.

For both translating and non-translating intermediaries, the intermediary has to save the entire frame so as to calculate Frame Error Rate (FER), which is used to dynamically control the transmit power of the mobile, so as to maintain a fixed FER per service.

B. Selection of the intermediary

In [1], we have assumed that the BS has a database of all the mobiles in its domain and decides on the intermediaries. The overhead is minimal, as a stretched connection is just a two-hop connection. The advantage of letting the base station choose the intermediary is that the BS has knowledge of speed, direction of motion of both MT and intermediary, based upon which it can optimize and select the best intermediary (in terms of low energy as well as stability to minimize the need for handoffs). Also, a BS can ensure the Quality of Service for an MT, by choosing appropriate intermediaries.

Unlike soft handoffs, which are initiated by the MT, the intermediaries and the BS handle the intermediary-to-intermediary handoff for the mobile. The intermediaries maintain an active list of mobiles in a direct connection, whose signal SINR exceeds the threshold setup for the connection. The intermediaries use the same mechanism of soft handoff, which maintain active, candidate, neighbor and remaining sets. But here, these lists contain sets of mobiles wishing to get their calls carried and not a list of Base Stations. The intermediaries repeatedly report the active list members in their dedicated control channels to the BS. The BS, which will receive similar information from other candidate intermediaries in the vicinity of the mobile, will run optimizations to select the best intermediary. It is assumed here that the BS transmits required information in the broadcast channel to enable the intermediaries to synchronize with the mobile's traffic channel. In [1], we used a greedy approach to select the best intermediary. Better Algorithms to determine the best intermediary are still under research.

C. Security

The security mechanisms in cdma2000 and UMTS differ. In cdma2000m, voice privacy is provided in the physical layer, whereas data privacy is provided in the link layer. In UMTS, both voice and data privacy is provided the link layer. Since voice privacy is implemented in the physical layer for cdma2000, the stretched model cannot be used for voice calls, as the intermediary will have to calculate FER for every frame, which means that the private data has to be decrypted. Since voice as well as data privacy is implemented in the link layer in UMTS, the stretched model can be used for both types of applications without affecting privacy.

D. Handoff

Within the duration of a connection, it is possible that the mobile is assigned to more than one Intermediary. In such cases, a handoff has to occur between intermediaries. Currently in 3G, FDD mode uses soft handoff and so more than one BS is involved during handoff. TDD on the other hand uses hard handoff and so only one BS is involved during handoff. This is because, the source and target BS' have different synchronization requirements and simultaneous reception or transmission with both the BS is not possible. Also, in TDD mode, the Resource Unit (RU) assignment, which is a combination of frequency and time slot assigned to the channel, can differ with both base stations.

In a stretched connection, both the source and target intermediaries relay the same information to the mobile. This works similar to soft handoff in FDD mode in 3G systems. Since the two Intermediaries belong to the same cell, both have similar synchronization settings. Since both intermediaries relay the same information to the mobile and so both use the same RU. Therefore, soft handoff is still possible in TDD mode for a stretched connection.

It is also possible that the mobile might not get a suitable intermediary or the intermediary wants to initiate a call during the ongoing stretched connection.. So, a handoff between stretched and direct connections can occur. We are assuming here that the BS maintains the direct connection of the mobile in a suspended state, so that it can be regained immediately in case of a stretched to direct handoff.

Since the distances from the MT to each of the intermediaries is much smaller than the distances from the mobile to source and target BSs, the signals from both the source and target intermediaries can be accommodated within the maximum allowed search window size. During handoffs, the signals from more than one intermediary can therefore be thought of as multipath of the same signal. So, there is no handoff seen for the MT, similar to repeaters [8].

E. Delay

The delay introduced in the intermediary depends on whether the intermediary is operating in translating or non-translating mode. The delay can range from twice the duration of a PCG to twice the duration of a frame. From [6], we see that the overall one-way delay from mobile to Public Land Mobile Network (PLMN) border is 100ms. Therefore, we can assume that the end-to-end delay is 200ms. For real time data, the allowable delay jitter is less than 250ms, while for voice it is 400ms [6]. Assuming that both call initiation and call termination ends of the connection are stretched and the intermediary does translation of the frame, the delay introduced in the connection is twice the duration of the frame length. If the frame duration is 20ms, then the delay in the initiation and termination ends of the connection is a combined 40ms, when a translating intermediary is used. The end-to-end delay thus increases to 240ms that is still less than the maximum limit of 250ms. Though the delay just satisfies the limit, by using shorter frames like in TD-SCDMA, where the frame duration is 5ms, the delay can be further reduced. For multihop relaying as in [4] and [5], the delay is variable.

The delay is much lower equal to twice the duration of a PCG, when a non-translating intermediary is used.

F. *Co-channel Interference at Intermediary*

The BS performs a closed loop power control, so that MTs transmit at a power, which is just enough to satisfy the BER requirements at its receiver. Power control is also done to prevent Near Far effect at the BS receiver. If both direct and stretched connections co-exist in the same frequency band, then the MTs with direct connection can interfere with the MT with a direct connection at the latter's receiver. Since the intermediary is much closer to the MTs near the vicinity of the stretched MT than the BS is, the signal power received at the intermediary from these direct MTs, will be much higher than that is actually received at the BS receiver.

To solve this problem, we can have a dedicated stretched connection channel. This requires hard handoff between direct and stretched connections. Alternatively, if TD-SCDMA is used, then according to [7], synchronization can be achieved using orthogonal codes for both uplink and downlink, as long as the two signals do not have a delay offset of greater than half a chip duration - For 1.25Mhz, it is around 125m. So, in case of microcells this is a feasible solution. If the original microcell had a radius of 125m, then with the stretched connection, it could have a radius of 250m, extending the range of the cell in the process.

G. *Absence of Diversity at Intermediary*

The BS provides diversity in the form of dual antennas, smart antennas, Multi User Detection (MUD), which reduces the required SIR requirements for a MT. But with relaying, if we are assuming MTs as intermediaries, then it is very costly to provide these diversity mechanisms in the intermediaries. In [1], we ran experiments to measure the energy improvements without diversity gain in the intermediaries, and we still found 2-7 times improvement in energy savings. Therefore, we can assume that relaying is still effective.

III. STRETCHED CALL MODELS

In this section, we discuss the various call models possible using the direction of operation of the intermediary, the duplex mechanism and traffic symmetry.

Bi-directional & Unidirectional Models: If the intermediary is used for both forward and reverse links for relaying, then the model is a bi-directional model. If the intermediary is used to relay either in the forward or reverse links, then the model becomes a unidirectional model.

Duplex Mechanism: The duplex mechanism used in the two arms of the Stretched connection, can be given in UA-LA (Upper Arm - Lower Arm) representation. The possible combinations in UA and LA are TDD-TDD, FDD-FDD, TDD-FDD, and FDD-TDD models.

The key observation we make here is that FDD mode is better suited for a given UA or LA if the propagation environment for that arm "varies" over the lifetime of the connection. If the propagation environment does not change, however, then the TDD mode is a better choice for that arm. In TDD mode, either transmission or reception is possible at any time, where as both transmission and reception is possible at the same time in FDD mode.

Traffic Symmetry: The traffic in the physical layer can be either symmetric or asymmetric. The traffic is symmetric when the application is a symmetric one like voice or video conferencing. It also becomes symmetric in high mobility scenarios when PCGs have to be sent regularly as part of inner closed loop power control. The physical layer traffic is asymmetric in low mobility scenarios for applications like Internet browsing, uploads and downloads.

Each figure described in this section is divided into three parts. The top most part denotes the BS functionality - both transmission and reception. The transmitted packets are in solid lines, while the received frames or PCG are in dashed lines. The middle part denotes the Intermediary's transmission and reception, and the bottom part denotes the mobile's transmission and reception. Solid arrows indicate reverse link traffic while dashed arrows indicate forward link traffic. The unit of transmission is either a frame or a PCG, depending on whether a non-translating or a translating intermediary is used. PC refers to Power Control information that contains only power control updates, without data. A PC is contained in a PCG.

A. *Bi-directional Symmetric Models*

We can have FDD-FDD, FDD-TDD, TDD-FDD and TDD-TDD models.

1)FDD-FDD Model

FDD modes are suitable for symmetric traffic and high mobility scenarios (where the propagation environment changes rapidly), because both reverse link and forward link are active simultaneously and so fast power control is possible for each link.

One possible FDD-FDD model is shown in Fig. 1 Here, the intermediary compresses two blocks into one for both reverse link and forward link. By increasing the transmit power, the loss due to compression can be overcome. Depending on the coding rates, the number of frames that can be compressed varies. Alternatively, lower spreading codes for the stretched connection can serve as a compression method. In Fig. 1, the unit of transmission is a frame because the intermediary has to change the coding rate or the spreading rate.

We see here that the delay is more than twice the frame duration. This happens in the FDD-FDD models where compression is required. Without compression, the delay is equal to twice the frame duration. Also, using shorter frames as in TD-SCDMA can reduce the delay.

2)TDD-TDD Model

Fig 2 shows a symmetric TDD-TDD model. It differs from the FDD models in that the Mobile can either receive or transmit at any given time. This results in reduced throughput, and therefore a TDD-TDD model is not a suitable model.

3)FDD-TDD and TDD-FDD Models

In the FDD-TDD model FDD is used in upper arm and TDD in lower arm. The FDD and TDD operating frequencies are different and therefore the upper and lower arms use different frequencies, which requires frame translation at the intermediary. It should be noted that the frame structures are also different for FDD and TDD modes. The TDD arm can support only low mobility environments.

A possible FDD-TDD and TDD-FDD Symmetric model can be constructed by combining Fig. 1 & Fig. 2 (space constraints force us to leave out this figure). Since these involve TDD arms, they are not suitable for "symmetric applications", but only for asymmetric applications. These models are modified versions of TDD-TDD arms, with FDD used in place of TDD in one of the arms that has a changing propagation environment.

B. *Bi-directional Asymmetric Model*

An asymmetric model is suitable only for a TDD-TDD or an FDD-TDD or a TDD-FDD model. The use of FDD-FDD model for asymmetric data results in wastage of spectrum in either direction, which does not relay traffic. While TDD-TDD model is suitable for non-changing propagation environments in both upper and lower arms, FDD-TDD models are suitable for predominantly uplink traffic. This is because with low mobility in the lower arm, the MT has to only transmit data without the need to receive frequent PCGs. In the upper arm, the intermediary can send PCGs to BS along with the uplink data, but also simultaneously receive PCGs from the BS. This is possible as the upper arm operates in FDD mode. Similarly, a TDD-FDD model is suitable for a predominantly downlink traffic.

C. *Unidirectional Models*

For unidirectional stretched connections the intermediary transmits only in one direction and therefore, it does not have to time multiplex transmissions to BS and MT. Only the direct forward link unidirectional model is useful, since power savings in the MT can be achieved.

1)FDD mode with Direct Forward link

A possible model is shown in Fig. 3. This model is suitable for both symmetric and asymmetric models with low mobility. In the reverse link, the MT and intermediary send data continuously, while in the forward link, transmission from BS includes transmission to the intermediary and the mobile.

In a changing propagation environment, power control updates have to be sent from the intermediary to the MT. This reduces the throughput of the connection, since the intermediary is sending PCG frames that could be used for data. In the reverse link, the MT can send power control information to the BS via the intermediary along with sending data to the intermediary. In the forward link, the BS has to send PCG frames to both intermediary and MT.

In a non-changing propagation environment, the PCGs can be replaced with data and higher throughput is achievable even for symmetric traffic. Two frequencies, one for the lower arm and the other for the upper arm and the direct call are required because the BS has to transmit power control updates to the intermediary and data to the MT in case of symmetric traffic.

2)TDD mode with Direct Forward link

Since the distances from the MT to the BS and that from the MT to the intermediary are different, the timing synchronization is different for both. Therefore, this model is not suitable for unidirectional models.

IV. SUMMARY: CHOICE OF MODEL

Based on the metrics of throughput and delay the best models differ. The criterion that affects throughput is the multiplexing of transmission to UA and LA by the intermediary, when either the traffic is symmetric or when there is high mobility. If the intermediary transmits only data with or without PCGs, and not explicit PCGs, higher throughput can be achieved. The following models satisfy these criteria:

Low Mobility Symmetric: Unidirectional model in FDD.

Low Mobility Asymmetric: Bi-directional TDD-TDD, FDD-TDD and TDD-FDD.

High Mobility Symmetric: Bi-directional model in FDD.

High Mobility Asymmetric: Bi-directional model in FDD.

If the intermediary is a non-translating type, then a delay equal to the duration of a PCG slot is incurred. If the intermediary is a translating type, then a higher delay equal to the duration of a frame is incurred. The delay here refers to the additional time incurred for a PCG or a frame to reach the BS. The following models satisfy for a low delay non-translating intermediary:

Low Mobility Asymmetric: Unidirectional FDD model, and all bi-directional modes.

If one of the arms has a changing propagation environment and the other arm has a non-changing propagation environment, then the latter arm can use TDD mode, while the former arm can use FDD mode. A TDD-FDD model is suitable for predominantly downlink "application traffic", while FDD-TDD mode is used for predominantly uplink "application traffic".

As discussed in Section II, voice traffic cannot be relayed using cdma2000. Also, since only FDD mode is mentioned in the specifications, FDD-FDD modes can only be used. As both FDD and TDD modes are used in UMTS, all the models mentioned above are feasible. TD-SCDMA is very encouraging, as it can reduce co-channel interference at the intermediary and can reduce the delay in translating modes.

V. CONCLUSIONS

In this paper, we have discussed how relaying can be implemented in 3G cellular networks. Though relaying provides improvement in capacity, coverage, throughput and energy savings, it introduces new problems. We discussed how the problems like increased handoff, selection of intermediary, absence of diversity at the intermediary, and co-channel interference at the intermediary could be resolved. We showed various models using the combination of duplex mechanisms to derive the best models that provide highest throughput and least delay characteristics.

VI. REFERENCES

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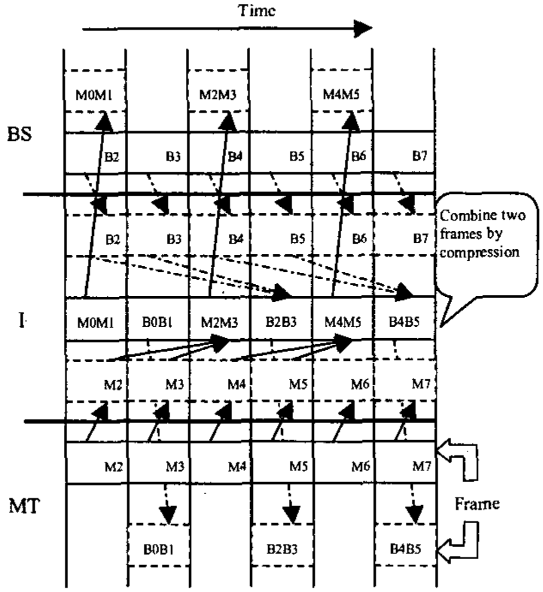

Figure 1. FDD-FDD Symmetric Model with Compression

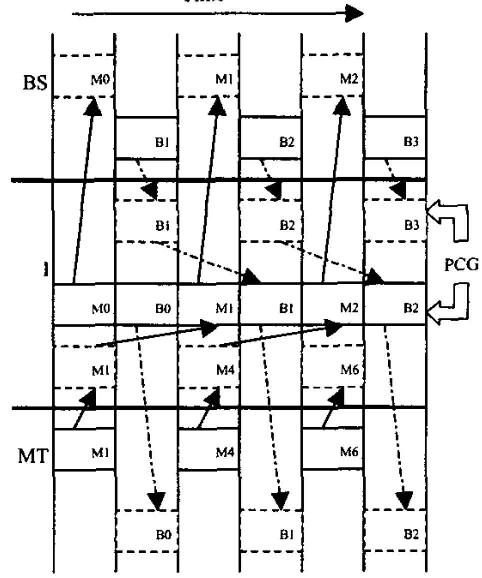

Figure 2. TDD-TDD Symmetric Model

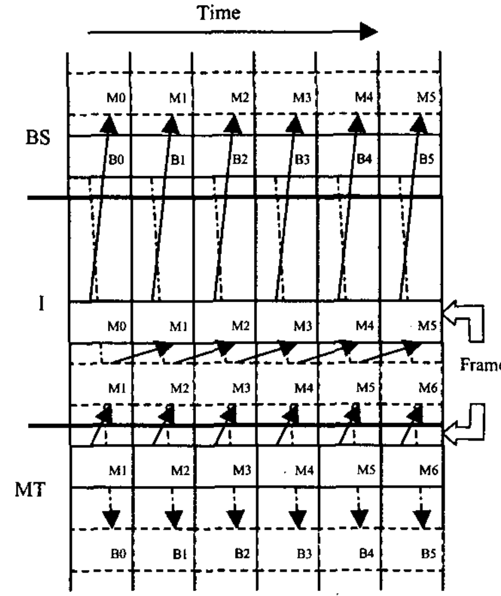

Figure 3. Unidirectional FDD Model with Direct Forward