Relay Network Extension on Wireless Access Links (ReNEWAL) of High Rate Packet Data (HRPD)

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***Abstract*—A novel method of architecting relay functions, within the paradigm of frequency division duplex based cellular networks, by modifying the access terminals (AT) to AT Relays (ATR) and enhancing HRPD access networks (AN) is proposed. Traditional applications such as spot/emergency coverage, and new applications related to network auto-configuration, optimization, and fault management are supported.**

Two bi-directional data streams are supported concurrently within a single AT radio aided by relatively simple enhancements to power and resource allocation mechanisms at the AT/AN, and interference cancellation at the AN to reduce blow-back to the data-sourcing ANs from the forwarding ATRs. A self-routing and self-configuring backhaul capability is created with a new flow type, and by adding a new request-response route-discovery protocol. ATRs can be consumer owned, for which an incentive negotiation model for cooperation is defined, or infrastructure owned. Extensions to multi-carrier systems and comparisons with IEEE 802 relays are discussed.

***Index Terms*—Access Terminal (AT), Base Transciever System (BTS), Relay, Access Terminal Relay (ATR), Radio Access Network (RAN), High Rate Packet Data (HRPD), Frequency Division Duplex (FDD), macro-, pico-, femto-cells.**

TABLE I
ABBREVIATIONS, ACRONYMS, AND TERMS

AODV	Ad-hoc Distance Vector
AT	Access Terminal
ATR	AT Relay
BS	Base Station (equivalent to BTS)
BTS	Base Transceiver System
CAPEX	Capital Expenditure (cost of equipment, infrastructure, hard- -ware, and software)
CDMA	Code Division Multiple Access
DHCP	Dynamic Host Configuration Protocol
EVDO	Enhanced Voice Data Optimized
FDD	Frequency Division Duplex
HRPD	High Rate Packet Data
IP	Internet Protocol
OPEX	Operational Expense (cost of maintenance, repair)
RNC	Radio Network Controller
RIP	Route Information Protocol
TDM	Time Division Multiplexing
TDD	Time Division Duplex
UMB	Ultra Mobile Broadband

I. INTRODUCTION

At the present time, wireless network coverage of traditional low data rate voice services extends to majority of the highly populated urban and suburban areas around the world. A traditional wireless access network infrastructure consists of a number of BTSs (access points) connected to a centralized controller (radio network controller/BTS controller) using wired links (copper, co-axial cable, fiber). The radio network controllers are connected back to circuit-switches or packet-data routers which in turn connect to the wired telecommunications infrastructure or the core network, as depicted in Fig. 1. In the coming years, the actual numbers of infrastructure nodes (BTSs or access points) is likely to increase by one or two orders of magnitude. Typically, large service provider networks have deployed in excess of $50,000$ cells sites at which BTSs are located. It is not unrealistic to expect such numbers to grow by a factor of 100 to about 5 million. Such large number of BTSs will be needed to ensure ubiquitous coverage including extensions to rural areas and indoor areas.

The projected increases in the number of BTSs poses two major challenges: wiring each of these new base-stations to the core network, and managing these networks. In current networks, the backhaul wiring costs are a large proportion of the infrastructure capital expenditure (CAPEX). The operational expenses (OPEX) associated with managing the emerging complex, and geographically spread-out, networks are also a key concern to service providers.

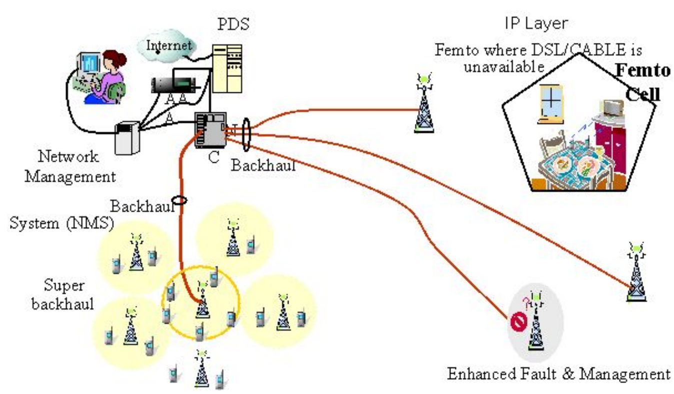

Fig. 1. Some Use Cases.

It is also likely that many of these new access points cannot be easily supported with a wired backhaul to the core network. This is especially true for rural areas where the cost of running a wired backhaul to each BTS is prohibitive, thus requiring a backhaul free "unwired" base-station solution. A second area of significant potential growth is Femto cells —

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consumer owned base-stations that provide coverage within a single home. While many Femto cells will be wired to the core network via a DSL or cable modem connection, there is significant scope for providing "unwired" Femto cell solutions where a high speed backhaul connection to a home is unavailable.

With the ever increasing complexity, heterogeneity of network elements, and co-existence of multiple air-interface technologies, leading to complicated radio network interference control and management issues, overall network management is of major concern. Thus, there is a need for autonomic or self-organizing capabilities to automate majority of the network management burden. This is driven by a need to reduce expensive and difficult manual intervention by technicians to install, maintain and operate the networks, as it is done for the most part today.

This paper describes a solution to the above problems of providing "unwired" connections and facilitating automated network management that is relatively simple to implement, with few extensions to existing air-interface and higher layer protocols that can fit within the paradigm of existing frequency division duplex (FDD) cellular networks — which are the vast majority of the deployed networks worldwide [1]. We contrast our novel inexpensive solution with other stand-alone overlay networks based on IEEE 802 standards, which are potentially more expensive and harder to deploy and manage in such a context. This paper presents the widespread CDMA based HRPD FDD air interface as a special case study. OFDMA and TDD based air interface relays have been described in [2]–[4] among others.

In section II, we highlight a few key "unwired" deployment and network management problems that are addressed by the solution being proposed in this paper. Section III outlines the basic solution, in the context of HRPD, and compares it with other IEEE 802 based solutions. Section IV describes the enhancements at the various protocol layers including physical and media access control of HRPD as well as connection control and routing methods. In section V, a service model is described that allows the service providers to harness the power of millions of users to cooperate with the network for mutual benefit. Section VI explores, very briefly, the various modes of operation of relay networks, and points to studies related to spectral efficiency optimality, and where our solution fits in. In section VII, extensions of our scheme to layer-3 routing options in flat IP networks, as well as to multi-carrier air-interface technologies are outlined. Finally, concluding remarks are provided in section VIII. Appendix A provides an abstraction of the ATR network model which can be used to describe and construct any type of wireless network — from traditional cellular networks, to relay networks and mesh networks.

II. Some Challenges in Deployment and Network Management

This section expands on a few key scenarios and use-cases for "unwired" BTS deployment that can reduce CAPEX significantly. These include, but are not limited, to the following:

- Range extension: In-building and external cellular coverage extension.
- Temporary Spot coverage: Emergencies and Special events (sports, conventions etc).

To facilitate automated network management, as a step towards autonomic networks or self-organizing network capability, the following key areas are critical to the success of these new networks.

- RF Optimization and Configuration: Femto, Pico, and Macro cells cases.
- Fault and Performance Management.

A. Range Extension and Super backhauling

When range or coverage extension to spots with low traffic density is desired, it would be wasteful to deploy an expensive backhaul. Under these circumstances, it is desirable to have a mechanism that would allow simple and inexpensive deployment of these additional BTS's.

An extension of the above case is that of super-backhauling. Super-backhauling refers to a case where multiple BTS's, each having relatively low traffic and hence not warranting the expense of a dedicated backhaul, can somehow funnel their traffic through to a single common node for multiplexing them on to a single high speed backhaul. Thus, a single backhaul is shared amongst several BTS's.

B. Temporary Spot coverage

Very often, there is a need to set up and operate a wireless cellular network to provide temporary services. This scenario may occur during emergency situations where existing cellular coverage may not have sufficient local capacity and coverage to support all the emergency personnel needs. But more often, there is a need to support conventions, sports arenas, concerts etc, which only require a temporary coverage for a very large number of spectators or audience. It may be very expensive to have a dedicated infrastructure in place for these occasional events that may draw large crowds for a short duration.

C. RF Optimization and Configuration: Femto, Pico, and Macro-cell cases

As millions of pico and femto cells get deployed, configuration and optimization of pico and femto cells will place a major burden on service providers and end users alike. The various combinations of RF interactions i.e. macro-to-pico, macro-femto, femto-femto, pico-femto etc. need to be managed efficiently with minimal technician and end-user effort. Minimizing interference to macro cells and optimizing femto/pico coverage can be time-consuming, especially if they happen to be on the same carrier. A mechanism that allows for simple macro-cell base-station communication to co-ordinate the configuration and optimization with the femto/pico cell would be highly beneficial.

A frequently encountered field issue is the absence of a backhaul during initial base-station installation. Optimization of RF assets requires a subsequent site-visit after a backhaul becomes available, adding to the operational expense. If a mechanism exists whereby a new BTS without a functioning dedicated backhaul can be made to operate via an existing neighboring BTS backhaul, then this would alleviate the need for repeated and costly site visits.

D. Fault and Performance Management

OA&MP activities exact large operational expenses from wireless network operators, and lead to reduced availability and reliability metrics.

Availability, reliability, time-to-respond during emergencies and faults as well as operational expense are key concerns for service providers and network operators.

During certain class of fault conditions, as when heartbeats are lost between base-station and the network, trouble-shooting and fault isolation becomes a significant problem. This can only be accomplished by sending a technician out to the cell site, which may often take significant time, effort and expense.

The next section describes the solution strategy that can be exploited to solve the above mentioned field issues.

III. Solving the Problem: An Approach for Integrating Backhaul and Mesh Capabilities in the Radio-Access Network

When addressing a problem such as that of inter-BTS wireless connectivity described above, the obvious answer that suggests itself is dedicated point-to-point microwave links operating on separate spectrum. Aside from the issue of duplicative hardware required for this purpose, it would seem intuitive that a separate allocation of spectrum for backhaul would be less efficient than a scheme that re-uses the spectrum available for access. This leads to considering the alternative of BTSs using the access spectrum itself for backhauling traffic. In an FDD system this means a BTS wishing to communicate with another BTS must flip it's transmit and receive frequencies. During this time however, the BTS (acting effectively as an access terminal) is unavailable for access, and this too implies a inefficient utilization of system resources. Recognizing that, in an FDD system, the issue is one of frequency conversion, leads us naturally to consider the access terminal as a candidate for performing this frequency conversion to effect inter-BTS communication, without needing to time-share resources between access and backhaul.

In the remainder of this section, we describe the basic access terminal relay solution, and provide a qualitative comparison with other approaches to mesh networking and relays.

A. The AT Relay Model

We start with a basic definition of AT Relay (ATR) operation. When the access terminal sources (or is the final destination of) the information being communicated over the air between it and a BTS, the link is being used for access. When the access terminal is the recipient of the information (from another BTS) that it communicates over the air to a BTS, it is performing a mesh/backhaul/relay function using the very same air-interface resources and access protocols.

Two basic configurations of the AT Relay are possible, and illustrated in Figs. 2 and 3. In configuration 1, the AT Relay

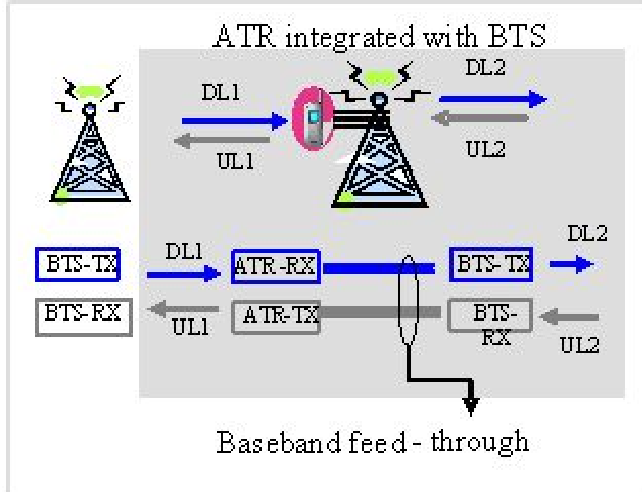

Fig. 2. AT Relay Configuration 1.

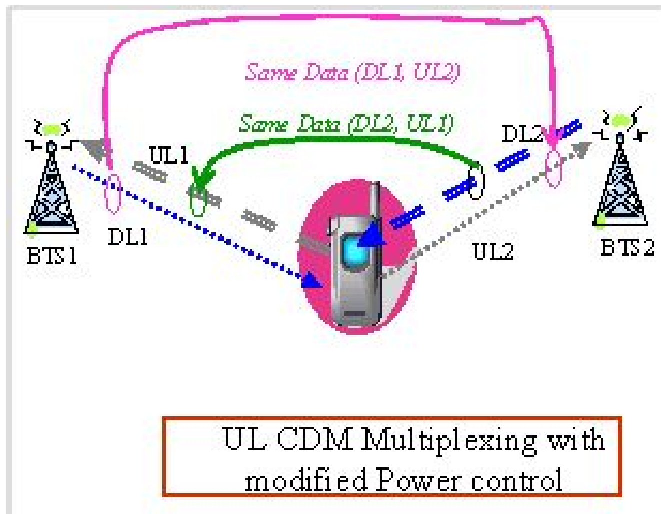

Fig. 3. AT Relay Configuration 2.

is wired to one of the BTSs and communicates over the air with the other BTS. In configuration 2, the AT Relay receives and transmits (at least) two bi-directional data streams over the air. Each BTS communicates with the AT Relay as it would if the AT Relay were the source/destination of the data being transferred.

The traffic being relayed by the AT Relay is assumed to be sourced/terminated at an AT that is communicating with BTS2, and thus the AT Relay — BTS2 combination is part of a range/coverage extension solution. The second configuration offers improved power efficiency over the first configuration (the power for relaying being split between the base station and the ATR), while incurring increased delay due to the two wireless links traversed between the source and destination.

The basic protocol stack within the AT Relay in configuration Fig. 3 is created by essentially duplicating the existing protocol stack at the AT used to support bi-directional communication with a single BTS, and bridging these stacks at the application layer to support the relaying function. The configuration in Fig. 2 could use the same approach, or a simplification (the pass through of data illustrated in the same figure) due to the wired link between the AT Relay and a BTS.

Transmissions made to the ATR by each BTS are scheduled, as in the case of access traffic, so as to meet the QoS requirements of the particular traffic flow. Transmissions by the ATR targeted towards a particular BTS are regulated by that BTS, whether from a power control or scheduling perspective. Estimation of supportable data rates on each of its wireless links is made by the ATR with BTS assistance, and ensures matching of upstream (or in-bound, i.e to the wired network) and downstream (or outbound, i.e. towards the destination AT) data rates.

It should be noted that all of the above is accomplished using the single transceiver present in the ATR, and does not require any duplication in radios or RF chains. The above ATR capabilities are complemented by a packet marking and encapsulation mechanism at the BTS to ensure appropriate routing of the backhaul traffic.

B. ATR-Enabling HRPD Access Network Model

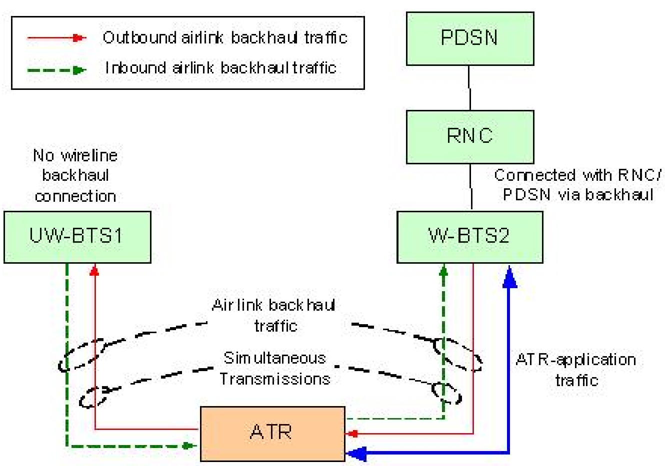

Fig. 4. AT Relay Network Model

Figure 4 shows a system model of a HRPD wireless network that enables ATR operation. In such an access network, there are conventional BTSs with wired backhaul connection (W-BTSs) to the RNC and PDSN, and additionally BTSs without wired backhaul (UW-BTSs). Such BTSs rely on ATRs to carry their backhaul traffic to the access network (AN) over the air link.

An ATR not only communicates with BTSs for traffic that it sources (or is the final destination for), but also backhauls traffic for the unwired BTSs.

The BTS with wired backhaul is the point of data ingress and egress from the wired network, and it is assumed that each unwired BTS knows at least one route to a wired BTS in its vicinity. Un-interrupted and reliable operation of this network is premised on the availability of ATRs to relay traffic between the unwired BTSs and a wired BTS. Since the goal is to minimize added complexity at the AT, the ATR here simply serves a relaying function, has no awareness of whether or not a particular BTS is wired, and does not actively route traffic.

C. The ATR vis-a-vis other relay solutions

Mesh networks fall under two major categories: a 2-tier mesh network, and a flat 1-tier mesh network. In the 2-tier mesh network, the first layer forms an interconnected set of mesh base stations. There are no changes to access terminals which continue to function in the normal mode. The access terminals do not have mesh capabilities. In the flat 1-tier mesh network, all terminals are capable of being a mesh node. There is no distinction between a base-station and an access terminal. Each node functions as both a base-station and an access terminal.

Representative relay solutions in the cellular context are described and analyzed in [5], [6]. The three main IEEE standards that deal with mesh and relay networks are 802.11s, 802.16j and 802.15.3/.4/.5 [7]–[13]. These are described very briefly to provide a basis for comparison with the ATR solution above. The two main mechanisms for resource allocation for data and signaling transfer between the various network elements in 802 mesh/relay networks are: Carrier sense multiple access with collision avoidance (CSMA/CA) and time-division-multiplexing (TDM)/time-division-duplex (TDD).

CSMA/CA is simply a listen-before-you-transmit mechanism. Each mesh point or access terminal waits to make sure that the channel is not being used by other mesh points before transmitting. The CSMA/CA protocol specifies how to deal with any collisions in case two mesh points happen to transmit at the same time. The CSMA/CA has the advantage of resource allocation not being controlled from a centralized node leading to easy deployment. The downside is the RF resources are inefficiently used.

In a TDD system, all the data and control is transferred on a single frequency. However, the time is divided into many small time-slots for scheduling and multiplexing (TDM) variable amounts of transmit and receive frames between various mesh/relay points. Typically, a centralized scheduler based resource allocation, either in base stations or special gateways, coordinates which network element transmits and receives at what time slots based on control information exchange between the various mesh points. The centralized resource management is simpler to implement, but slow and inefficient. Many distributed schemes, albeit much more complex, are being proposed as well.

A few key advantages for applying the ATR concept in FDD cellular network systems, as opposed to conventional mesh/relay solutions, are:

1) It is much simpler to build out a mesh/relay network with the existing two cellular network elements (i.e. BTS and AT) with minimal changes to the standards or device complexity.
2) It is expensive to have FDD mesh devices that can serve both as a BTS and AT, like in the 802 proposals, since essentially RF chains need to be duplicated.
3) The cellular resource allocation scheme (for access) is not collision based, and hence makes much more

efficient use of spectrum. The BTS makes resource decisions based on instantaneous demands and available resources. This also allows for *dynamic resource sharing* between the AT's own communication needs, and the need to reserve resources for backhaul.
4) Using separate 802 based mesh networks intertwined with cellular networks is operationally difficult to deploy.

IV. Enabling the ATR solution on HRPD

We now provide a detailed ATR solution in the context of the HRPD system, by addressing the following basic questions:

- Is it actually possible for an access terminal to become the means to integrate backhaul and access without significant changes to the way access terminals currently operate?
- What extensions are required to the existing access mechanisms and protocols to enable an end-to-end solution?
- How efficiently can such a relay operate?

A. Route Discovery and Setting up the Relay Path

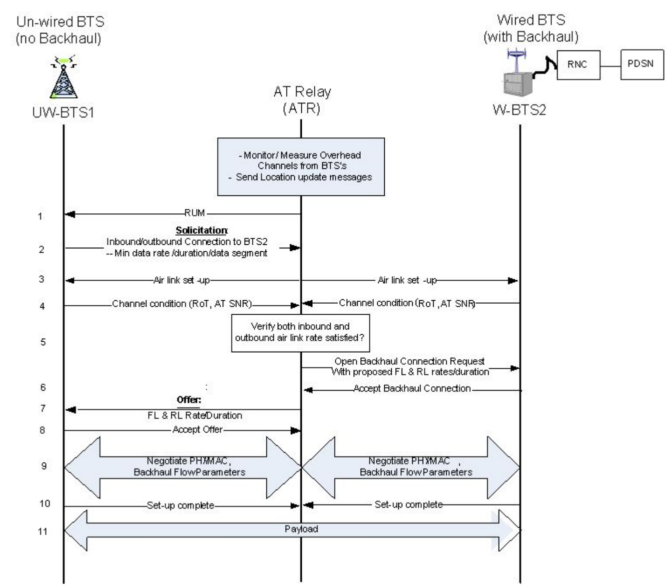

Fig. 5. Request-Response Model for Relay Set-up.

The call flow of Fig. 5 is intended to show how a bi-directional wireless link may be set up between an unwired base transceiver station and a wired BTS via an ATR. In this particular example, link set-up is initiated by the unwired BTS.

1) Following HRPD procedures, an ATR sends a Route Update Message indicating its presence to the unwired BTS. The contents of this message also indicate to the unwired BTS that the wired BTS is reachable via this ATR.
2) Assuming that the UW-BTS has data to relay (due to, say, an access attempt by another AT), it sends out a solicitation specifying the required inbound and outbound data rates, and duration for which it requires connectivity to the W-BTS.
3) The ATR, upon receiving such a solicitation, sets up connections to both the unwired and wired BTSs.
4) The two BTSs send the AT information (rise-over-thermal and pilot SNRs) that it needs in order to estimate the data rates that can be supported on each uplink. (Downlink data rates continue to be estimated by the ATR based on pilot measurements as in today's HRPD systems).
5) The ATR checks to see if the available data rates on the various links meet the outbound and inbound data rate requirements of the UW-BTS. If so, it sends an Open-Backhaul-Connection-Request to the destination W-BTS with the desired forward and reverse link rates and duration.
6) If the W-BTS accepts the request, it will send an acknowledgement message to accept the air link backhaul connection with the ATR's proposed rates and duration.
7) Upon the reception of the acknowledgement from the W-BTS, the ATR makes an offer to the UW-BTS specifying the data rates and duration.
8) The UW-BTS will send an accept message back to the ATR.
9) The two individual sessions between the ATR and each of the BTSs are now negotiated along with appropriate QoS parameters
10) After the air link backhaul configuration negotiation is completed, both source and destination sector will send set-up completed messages to the ATR.
11) Backhaul data can now be sent over the air link for both inbound and outbound traffic.

It can be seen that the wired BTS could just as easily solicit an ATR to connect to an unwired BTS.

In order to minimize the overhead of setting up ATR links, it is preferable for BTSs, both unwired and wired to maintain tables of active ATR links, and to re-use them subject to their meeting data rate and duration requirements. Such data rates, as well as durations, can be re-negotiated at any time to extend the lifetime of such connectivity.

The actual set-up of the end-to-end communication path is envisaged to be a protocol (relay or route set-up protocol) residing in the HRPD air-interface application layer. The protocol negotiates each BTS-BTS hop (it can take multiple hops to reach a wired BTS from an unwired BTS) and provides information to the intermediate BTSs that will ensure appropriate forwarding of the backhaul traffic, in either direction, to the correct end point (either the wired BTS, or the UW BTS serving the AT in question).

B. Routing between the Communication End Points

After the above request/response mechanism has set up an end-to-end communication path for relaying traffic, it remains to effectively transport traffic over the multiple air links making up this path (between the source AT and a wired BTS).

The packet marking and encapsulation scheme described below enables each BTS in the communication path to intercept and appropriately forward relay traffic. Further since

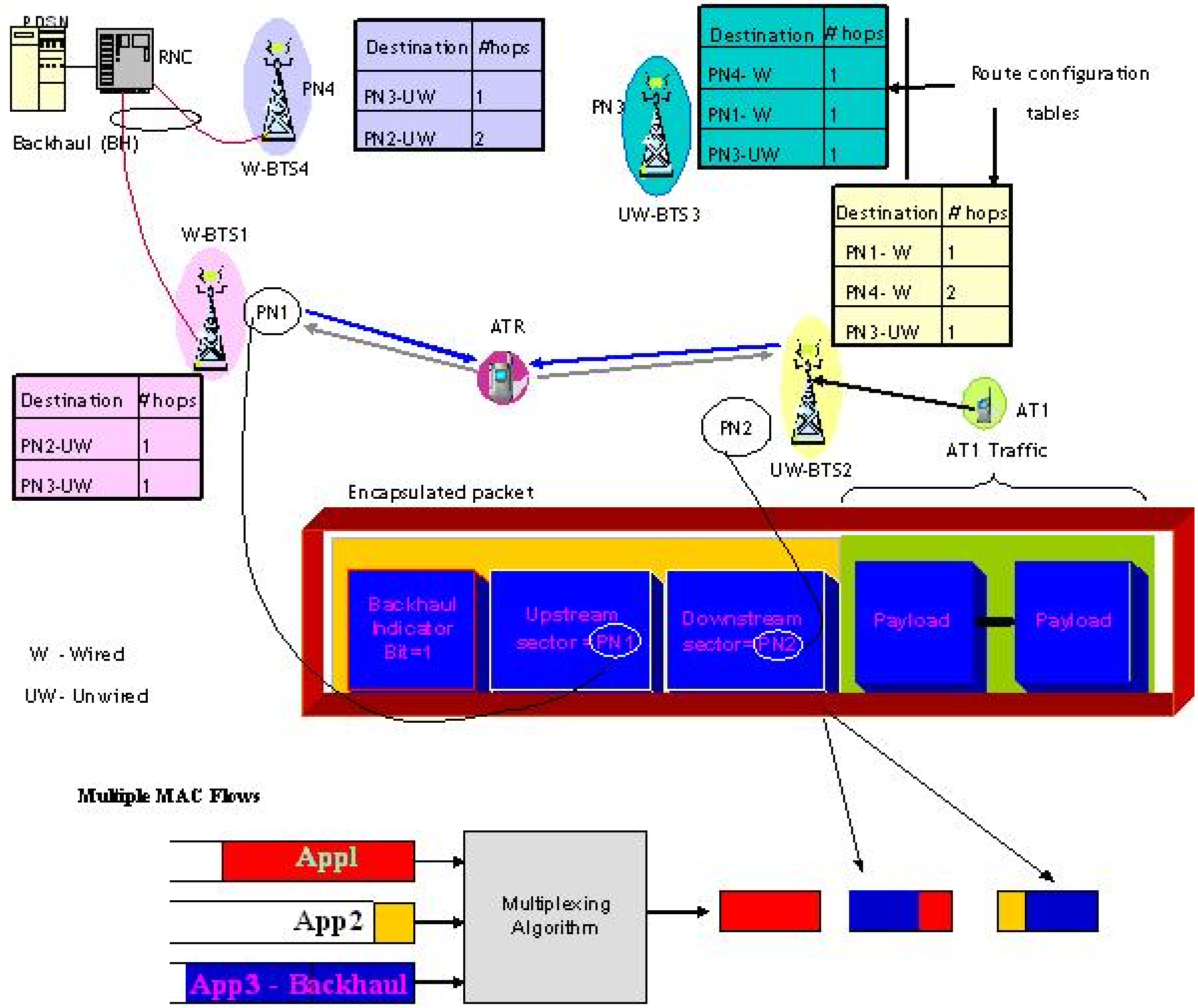

Fig. 7. Packet Routing.

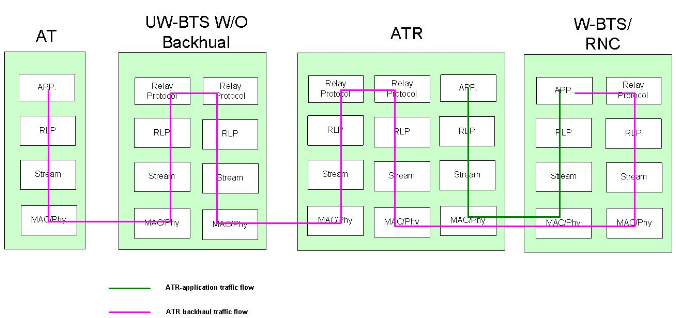

Fig. 6. Signal Flow through Protocol Stacks.

each ATR in the communication path may be simultaneously sourcing and relaying traffic, this mechanism also provides differentiation between these two types of flow. Appropriate end-to-end QoS of the relayed flows is also ensured.

The ATR relay protocol resides in the HRPD application layer (see Fig. 6), and encapsulates the relay (such as backhaul traffic) flows. It adds a bachaul (relay) flow indication at the packet header, as well as the source and destination BTS ID represented by the short PN code offset of the source and destination sector.

The key to the design of this protocol is the recognition of the intrinsic variability in the quality of each of the air-links that make up the end-to-end communication path. If the reliability assurance mechanism is placed at the path end points only, then a failure on any link causes the entire link to fail and requires retransmissions along the entire communication path. On the other hand, if reliable delivery is ensured over each such air link (every hop), then end-to-end QoS can be achieved with less delay and minimal retransmissions. Hence each air link hop will implement the entire HRPD protocol stack with the radio link protocol for reliable delivery over that link. The QoS treatment of each hop is determined by the forwarding BTS, and derived from the end-to-end QoS requirements of the application, coupled with the topology (number of hops) of the path.

As shown in Fig. 6, the ATR-Relay Protocol (which is invoked after the Relay Set-up Protocol has negotiated the end-to-end route) resides in the ATR, the wired and unwired BTSs. At each forwarding BTS, the protocol encapsulates packets with upstream (towards the wired network) and downstream (towards the AT) BTS IDs, and a marking that designated the traffic as backhaul traffic. Every receiving BTS intercepts, inspects, and forwards the flow either to the application (after removing the encapsulation), or passes it through (after replacing source and destination headers for the next hop) based on the presence of a backhaul indicator. At the ATR, the Relay Protocol uses the source-destination headers to correctly bridge the flow.

As shown in Fig. 7, a UW-BTS is provisioned with knowledge of all the neighboring W-BTSs and the routes to them, and maintains a table of these base stations. Similarly, a W-BTS maintains a table of the neighboring UW-BTSs. The BTSs are identified by their PN code offset. In this illustration, there is assumed to be at least one set of ATRs linking an UW-BTS to the local W-BTS. Route selection is a base station function, and there is flexibility with respect to the actual algorithm used to determine routes. For example, when UW-BTS2 receives the service request from AT1, it may decide to use the direct path to W-BTS1, solicit and negotiate a backhaul connection with an ATR located between it and W-BTS1. If such an ATR is not available, the UW-BTS may consider and negotiate alternate paths with multiple hops (ex: to W-BTS4 via UW-BTS 3).

C. Optimizing Radio Link Performance

The ATR (in the standalone configuration) is required to maintain two bi-directional radio links with a single radio. From a performance standpoint, high reliability is required since it is backhauling traffic on behalf of other users. Range must be adequate to span typical BTS radii. Further, the overall system must use radio resources efficiently.

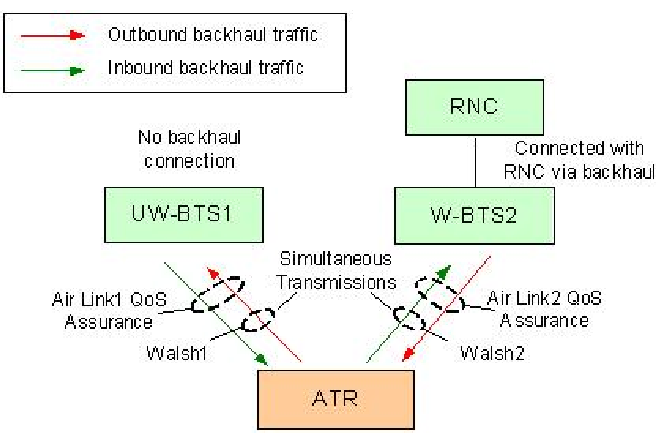

Fig. 8. Code Division Multiplexing of Data Streams.

1) Data Stream Multiplexing and Power Control: The HRPD reverse link is based on code-division multiplexing user transmissions. We extend this notion of inter-user code-division multiplexing to intra-user code-division multiplexing (Fig. 8). Thus the ATR, being required to transmit two (or more) data streams (to different BTSs), applies these streams onto separate (and orthogonal) Walsh codes. For single-path radio channels this will essentially eliminate the interference between the streams.

Further, in order to ensure successful reception of each stream at the base station towards which it is directed, the existing power control rule (or of the downs) is modified and each stream power controlled by the associated base station subject to overall AT transmit power limits.

Walsh codes are allocated to the streams in proportion to their transmission rates.

2) Range: Though a typical ATR will have the same transmit power limits as other ATs and is typically located at the cell edge, it is able to provide reliable inter-BTS connectivity, since the service parameters (data rates, duration) are negotiated during the set-up of the relay path. When ATRs are static and have Line-of-Sight visibility of the connected BTSs, they can also support up to two orders of magnitude higher data rates that typical mobile ATs that are constrained by fade margins and penetration losses. Further multiple ATRs can be used as relays between a pair of BTSs to ensure that per AT power constraints are not a limiting factor.

3) Interference Cancellation at Source and Neighboring BTSs: Since the typical AT is equipped with a single transmit antenna (and beam-forming technologies have not been deployed on HRPD BTSs), the ATR transmission directed towards each BTS necessarily blows back on the other. It was noted previously that the code-division approach to multiplexing data streams eliminated inter-stream interference under single-path channel conditions. However the base station receiver attempting to decode other ATs' transmissions still experiences the aggregate interference from these streams (i.e. including the stream which is directed towards a different base station). Using traditional successive interference cancellation techniques, the interference due to the stream directed towards this base station can be decoded (since this data stream is being power controlled by this base station to ensure successful reception) reconstructed and cancelled. However, this is not the case for the second data stream for which there is no guarantee of successful reception at this base station. In the following, we show how the deleterious effect of this data stream blow-back can also be effectively neutralized.

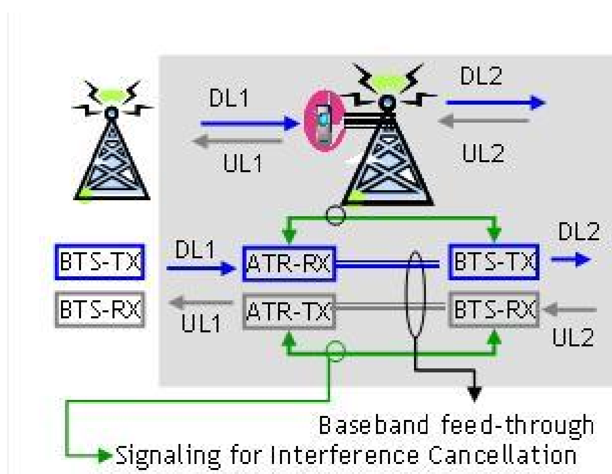

Fig. 9. Augmentation of ATR with Interference Cancellation — ATR Integrated with BTS.

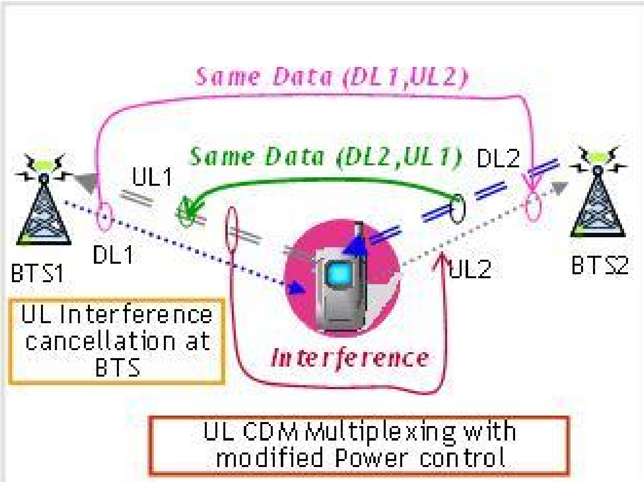

Fig. 10. Augmentation of ATR with Interference Cancellation — Standalone ATR.

The fundamental observation that drives the solution is the recognition that the signal blow-back to a BTS actually contains the very data that was sourced at that base station (and transmitted earlier on the downlink to the ATR). Figs 9 and 10 illustrate the basic approach to interference cancellation for both ATR configurations.

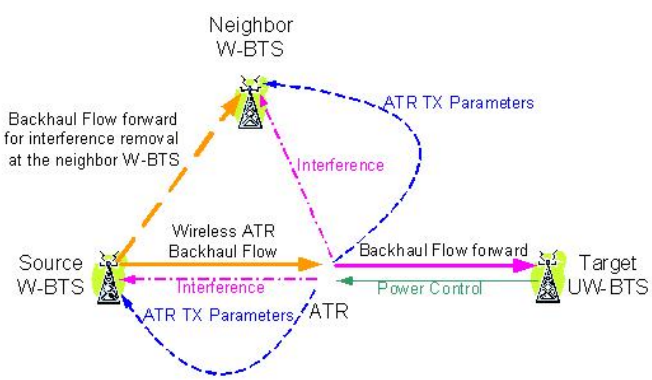

Fig. 11. Assisting Interference Cancellation at the BTS.

While the data component of the blow-back signal is known, the timing, coding and modulation of the transmission, i.e. the transmission parameters are unknown. Figure 11 illustrates how such transmission parameters may be relayed over the air so as to assist interference cancellation.

The second aspect of interference cancellation is that ATR transmission might, in some cases, cause interference at BTSs other than the one that sourced the data contained in the transmission. Fig. 11 illustrates how, in such cases ATR TX parameters could also be delivered to neighboring BTS through signaling links. The neighboring BTS does not of course have the source data to reconstruct the interference, and so, requires the sourcing BTS to relay this information to it over the wired backhaul.

It is expected though, that in most cases of ATR deployment, interference to secondary BTSs will not be an issue, and

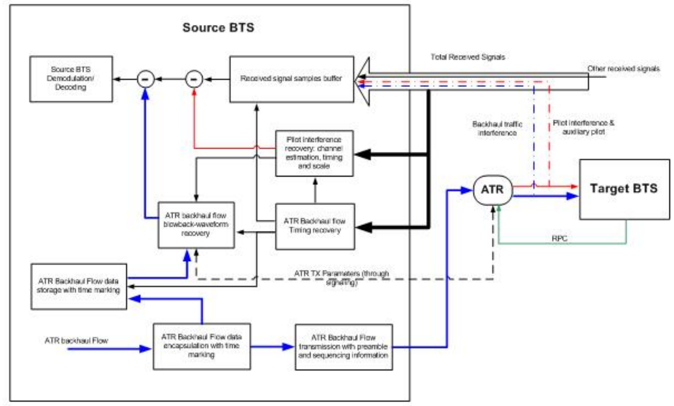

Fig. 12. Receiver for Interference Cancellation.

interference cancellation at source BTSs will be adequate to manage interference due to blow-back.

Figure 12 shows the block level processing within the source BTS receiver resulting in removal of the blow-back interference. Along with coding and modulating the data for over the air-the-transmission to the ATR, the source BTS also buffers sent data with appropriate time stamps (bottom left of the illustration). The received signal over the air is examined for the ATR's pilot signal and processed to recover an estimate of the channel between the ATR and the BTS (top right of the illustration). The pilot signal may also be removed for the received signal at this point. The central operation performed is the subsequent reconstruction of the blow-back signal using the pre-stored data, timing information, TX parameters, and radio channel estimates. The end result is nearly complete removal of the blow-back signal, and availability of clean signal that can be processed to recover data from other transmissions that are intended for this base station.

V. INCENTIVE/SERVICE MODEL

In order to provide such routing service (and enable BTS meshing/backhaul), the AT is leveraging its favorable location, i.e. the fact that it's current location enables it to transmit and receive packets reliability between a set of BTSs.

Frequently such locations may be the consumer's residence or work place, i.e. locations that are not accessible to a service provider for installing additional BTSs to extend coverage.

In effect then, the consumer (AT owner/subscriber to the wireless service) is providing a service to the network operator (service provider). The service model is therefore one in which the consumer is compensated by the service provider for providing connectivity services to the service provider. The compensation could include payments or credits towards future use of wireless access service.

Compensation to the consumer can be negotiated either as part of his service contract (i.e. corresponding to the duration of time the AT is at the customer's residence and therefore available as a relay), or during the actual time that the routing service is provided. In the latter case, ATs can either advertise their rates, or BTSs can indicate the offered rates, for relaying.

VI. Performance Considerations

The use of the access spectrum for backhauling will obviously reduce the capacity available for access. Is such a tradeoff worthwhile?

Taking a simple one-hop system as an example, where an ATR is relaying data to a UW-BTS serving other ATs, we recognize first that the ATR is using uplink capacity to relay downlink data via this base station. For downlink intensive applications, there is likely to be substantial uplink capacity available for the ATR, and so the system is more efficient than one where separate bandwidth is dedicated for backhauling. It should also be noted that with the approach to eliminating blow-back via interference cancellation described previously, the uplink cost of backhauling is effectively incurred at only one base station (the target UW-BTS, and not the source W-BTS). Finally, the use of successive interference cancellation allows the system to adapt to varying backhaul and access capacity requirements; the loss in access capacity being exactly offset by the gain in backhaul capacity and vice versa.

In a multi-hop environment, the backhaul costs are recurring (at every intermediate BTS node), and therefore can reduce the overall spectral efficiency of the system.

For networks with symmetric data rate requirements, multi-carrier systems can be leveraged to simply overall system implementation as will be discussed in the next section.

A heuristic argument in favor of an ATR based approach can also be made on the basis of information theoretic results pertaining to relays. Relays can be operated in three modes: Amplify-and-Forward (AF), Decode-and-Forward (DF) and Compress-and-Forward (CF). Each of these modes is applicable to certain specific deployment scenarios based on the relay's location between the source and target. The ATR can be though of as falling under the category of DF. It has been shown in [14], [15], that to obtain optimal spectral efficiency in DF relays, the relay placement should be close to the mid-point of the source and destination. This is naturally the case with the ATR. It should be recognized that the theory does not leverage interference cancellation in deducing these results and so the correspondence between these cases is not exact.

VII. Extensions

A. Layer-3 Relaying Options

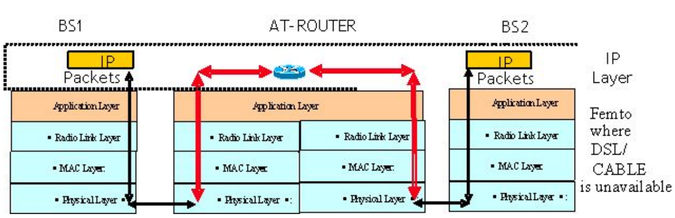

Fig. 13. AT Router.

Cellular networks are evolving to flat IP networks. Internet Protocol (IP) is already at the edge in next-generation networks, i.e. base stations are IP aware, and BTSs and ATs are IP addressable. The evolved air-interface protocols support internet protocols between these ATs and the BTSs. We now have another option by which to relay and route packets between BTSs via the ATs — add an IP layer routing capability at the ATs (in addition to such a capability at the BTS). This is depicted in Fig. 13.

L3 routing (at both BTSs and ATs) provides several advantages. It is possible to have very simple extensions to existing routing protocols, which have been widely studied in ad-hoc/mesh networking community [16], [17]. Briefly, we can add extensions to ad-hoc distance vector (AODV) protocols by adding additional radio aware metrics, extend use of routing information protocol (RIP) type "route advertisement", and use dynamic host configuration protocol (DHCP) type "lease time" to indicate the duration of AT-Router availability.

B. AT based Relays in Multi-Carrier Systems

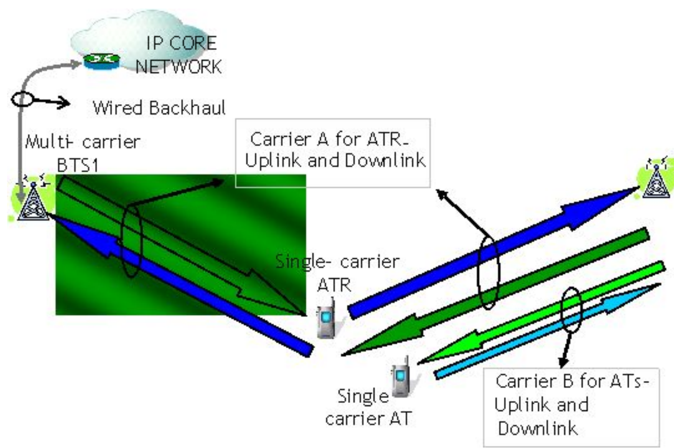

Fig. 14. HRPD Multi-Carrier (Rev B) Operation.

The next-generation air-interfaces, whether multi-carrier CDMA or OFDMA, lend themselves naturally to confining both intra-cell and inter-cell co-channel interference. Further, transmit and receive beam-forming capability at the base stations can further improve performance by confining spatial interference on the two legs of the inter-BTS communication (BTS 1 ▷ AT ▷ BTS 2) and make system performance on the uplink less dependent on effective interference cancellation.

Another aspect of multi-carrier operation is illustrated in Fig. 14. In this case multi-carrier operation can be leveraged to separate the transmissions to/from the ATR from those being made to/from ATs. In cases where the backhaul traffic requirements are symmetric, this approach can provide performance that is comparable to transmitting both backhaul and access traffic on the same carrier, with somewhat reduced interference cancellation complexity (only ATR blow-back needs to be cancelled).

ATRs on OFDMA systems may also rely on the BTSs (as opposed to the ATRs) to estimate the data rates that an ATR can support (as part of the route set-up), since the necessary information to do so is currently sent by ATs to the BTSs as per these standards [18].

VIII. Concluding Remarks

The proposed AT Relay based extension of HRPD networks is a spectrally efficient way to extend the coverage of such networks for both rural and indoor deployments, as well as for network management purposes. The extension of HRPD protocols to support AT relays appears to be straightforward, and does not significantly increase AT complexity. While the solution has been detailed in the context of single carrier HRPD systems (specifically Rev A), it appears to be easily extensible to multi-carrier air-interfaces as also future flat IP networks.

Appendix

Abstract Network Model

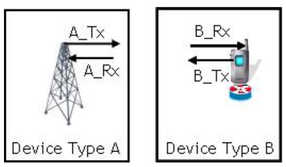

Fig. 15. Abstract Network Model.

The abstract network model is one where there are only two device types which can be designated Dev Type A and Dev Type B. This is illustrated in Figure 15.

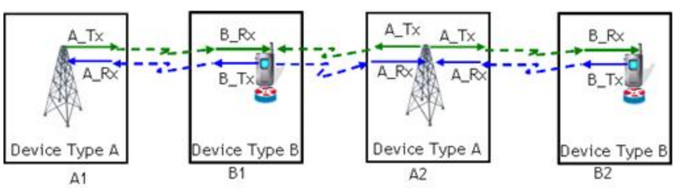

Fig. 16. MESH Network.

The network operation is defined by the following rules:

1) Dev Type A operation is complementary to Dev Type B
a] For example, in a Frequency Division Duplex (FDD) System, the transmit and receive frequencies of these two device types are flipped. In Fig. 15, transmit frequency A_Tx is equal to receive frequency B_Rx and frequency B_Tx is equal to frequency A_Rx for effective simultaneous transmission and reception to occur.
b] In Time Division Duplex (TDD), a single frequency is used, and hence simultaneous transmission and reception cannot take place. Therefore, the transmit and receive time-slots are flipped. Each device must listen while the other is talking for establishing any reasonable communication between them. If both devices attempt to transmit at the same time, a collision occurs and no effective communication takes place. Again referring to Fig. 16, when device type A is transmitting at time-slot A_Tx, the receiver in device type B must listen to it at the same time B_Rx. Similarly, when device type B transmits at time slot B_Tx, then device type A must listen to it at the same time-slot A_Rx.
2) A device type does not communicate directly over the air (i.e. without any intermediate nodes) with another device of the same type.

Thus all communications are of the type

$$\text{Dev Type A} \Leftrightarrow \text{Dev Type B}.$$

Two devices of Type A communicate via a Dev Type B:

$$\text{Dev Type A (1)} \Leftrightarrow \text{Dev Type B} \Leftrightarrow \text{Dev Type A (2)}.$$

Fundamentally, any type of network — traditional point-to-multipoint cellular networks, mesh or relay — can be devised using just these two types of network elements of opposite Tx/Rx polarity.

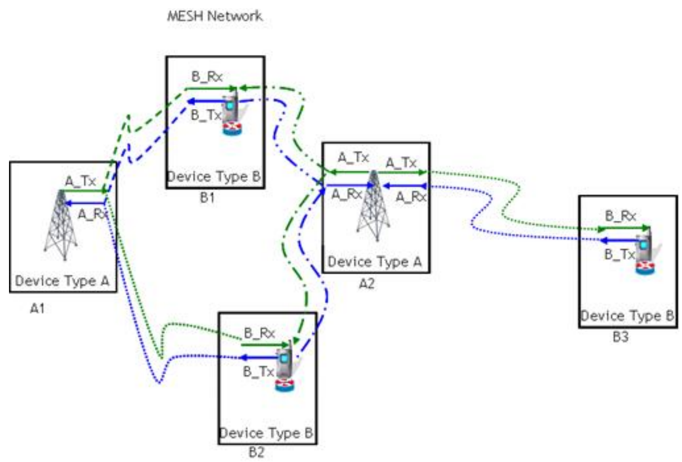

Fig. 17. Possible Mesh connections between Devices A and B.

When mapped to traditional cellular systems, one can see that this system allows any two BTSs to communicate with each other using intermediate ATs and BTSs, as also any two ATs to communicate with each using only the services of intermediate BTSs and ATs (i.e. without the use of any wired of specialized wireless backhaul). Such an all-wireless network is also illustrated in Fig. 17.

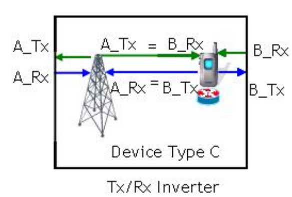

Fig. 18. Type C Device.

If needed, a Device Type C can be derived by integrating two devices of Type A and B as shown in Fig. 18. The wired interface between Device Types A and B, within Device Type C, are the same as the wireless interface. From an external perspective, Devices of either Type A or B can communicate with Dev Type C as shown in Fig. 19. Interference between the constituent device types in Dev Type C can also be mitigated by the use of interference cancellation techniques since the information content of the interfering signal is known *a-priori*. In essence, this device acts as a Tx/Rx inverter.

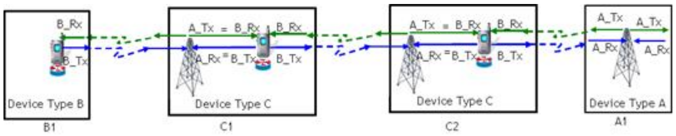

Fig. 19. Network created using Device Types A, B, C.

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