Connecting Mobile Phones via Carrier-Grade Meshed Wireless Back-Haul Networks

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Abstract. Meshed wireless back-haul networks are seen as an affordable technology to bring Internet connectivity into rural and previously unconnected regions. To date, the main focus is to provide access to classical services such as the WWW or email. Access to such services requires the users to use a personal computer or a recent smart phone. Especially in developing regions, the prevailing end user device is a mobile phone. In order to connect mobile phones to an IP-based back-haul network, the network access points must provide a mobile phone air interface which is usually based on GSM or UMTS. In order to avoid dependence on a costly 3GPP infrastructure, we propose to deploy GSM or 3GPP nano cells in order to terminate the mobile phone protocols immediately at the mesh access points. Hence, the voice or data traffic can be carried over IP-based networks using open protocols such as SIP and RTP. In this paper we present a meshed wireless back-haul network with access points that have been equipped with GSM nano-cells. The voice traffic generated by the mobile phones is carried across the mesh in parallel to typical web or video traffic. In this paper we evaluate the QoS handling received by the voice calls across our multi-hop wireless testbed and show that our architecture can provide the resource isolation required to offer uninterrupted VoIP services in parallel to typical Internet traffic.

1 Motivation

Wireless Mesh Networks (WMNs) have matured considerably and their visibility attracts researchers as well as commercial service providers. Resilience, self-configuration and maintenance combined with potentially lower equipment as well as operational costs are seen as major advantages compared to traditional commercially operated wireless networks. Especially in emerging or so far unconnected regions, WMNs have the potential to serve as a cost-efficient solution to bridge the digital divide. The lack of access to the worldwide communication infrastructure in emerging countries is a limiting factor for their improvement in education, health and economics.

The majority of potential customers in developing regions owns a mobile phone, but no personal computer. Therefore it is crucial to enable regular mobile

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phones to directly connect to the network, without the need of any additional software or modification on the mobile phone. However, in Africa for example the geographical conditions make a typical GSM deployment like it has been done in Europe or North America very expensive, since especially in rural areas the distances between villages are rather large, typically in the scale of several hundred kilometers. Thus, a regular GSM cell would cover only a comparable small number of customers which makes it unprofitable for most common operators. We therefore propose a new network architecture that incorporates nano-Base Transceiver Station (BTS) cells which are connected with each other and to the Internet via a Wireless Back-Haul (WiBack) network.

2 Architecture

WiBack builds upon the architecture defined by the EU FP7 project CARrier grade wireless MEsh Network (CARMEN)[3] which is based on an extended version of the IEEE 802.21 standard on the control plane and a light-weight implementation of Multi Protocol Label Switching (MPLS) [11][10] on the data plane. The access point nodes have been fitted with GSM air interfaces terminating the mobile phone protocols right at the access point so that the VoIP traffic can be forwarded via the mesh using open protocols such as Session Initiation Protocol (SIP)[12] in combination with Real-time Transport Protocol (RTP)[13] or alternatively Inter-Asterisk eXchange Version 2 (IAX2)[9]. In the following sections we will summarize the WiBack architecture and then describe the integration with the GSM air interface.

2.1 Carrier-Grade Wireless Back-Haul Mesh Network

The WiBack architecture builds on proven standards which have been extended to support heterogeneous wireless technologies. The core of the control plane adopts and extends IEEE 802.21, which allows for a hardware-independent and modular cross-layer architecture design, see Figure 1. The network management components such as the Topology Management Function (TMF), Routing, Monitoring and Mobility Management can be implemented as modules on top of an abstraction layer using the IEEE 802.21 messaging mechanism. This differentiates our approach from typical Network Layer routing protocols, which integrate similar functionality in one protocol and are often agnostic to physical hardware capabilities.

2.2 IEEE 802.21

One of the main goals of IEEE 802.21 is to provide link layer intelligence and abstraction for the upper layers. This should allow for a more intelligent decision making capability leading to more reliable and efficient hand-overs between heterogeneous access networks. However, the concepts and architecture of IEEE 802.21 can also be exploited for other purposes besides hand-overs such as

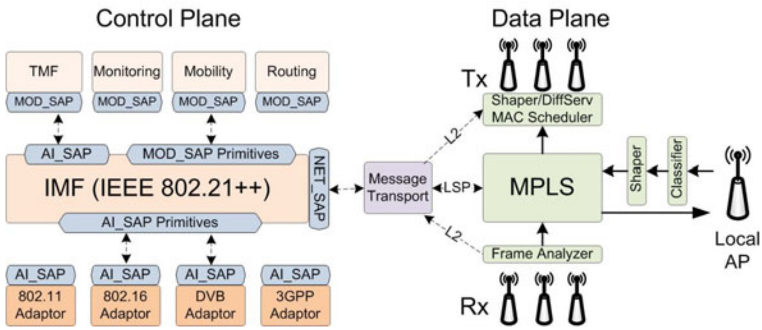

Fig. 1. IMF extends the IEEE 802.21 MIHF by Module-to-Module Communication

the management of heterogeneous networks including security, emergency services and power management relying on the resilient messaging characteristics specified in the IEEE 802.21 standard. Each of those topics have been studied within sub-groups of the IEEE 802.21 working group with the target of preparing amendments to the standard.

The IEEE 802.21 messaging service as well as the majority of the defined primitives can also be utilized for non-hand-over related purposes, such as managing local and remote radio technologies in a media independent manner. Therefore, WiBack builds on the general IEEE 802.21 architecture introducing new primitives or messaging service extensions where needed.

As depicted in Figure 1, the WiBack Interface Management Function (IMF) extends the IEEE 802.21 Media Independent Handover Function (MIHF) with primitives specific to wireless network management, therefore the name IMF has been chosen to reflect its responsibilities which go beyond *Media Independent Hand-overs*. This amendment to IEEE 802.21 provides a single interface for realizing Mobile Terminal (MT) hand-overs as well as building and managing a heterogeneous wireless networks.

2.3 Network Resource Management

Traffic Engineering (TE)[2] deals with network engineering and performance evaluation. It's objective is to facilitate reliable network operation. WiBack is designed upon traffic engineering principals which have been adapted to the requirements of volatile wireless links.

The resource utilization can be configured according to operator policies. The standard configuration builds on the over-provisioning paradigm to avoid queueing and loss inside the mesh network. Hence, at the ingress nodes, traffic is classified and shaped to fit into the envelope of admitted resources. The forwarding function at each intermediate mesh node performs prioritized DiffServ-like queueing as well as proper shaping to smooth out transient states of congestions due to traffic bursts, etc.

Constraint based routing computes paths through a network topology fulfilling a set of constraints. Instead of simple hop count metrics those constraints maybe be expressed as minimum bandwidth, maximum delay, or similar. To optimize the network resource utilization, the Path Computation Element (PCE)[4] architecture uses centralized routing entities.

Unlike hierarchical prefix routing which is typically associated with Internet Protocol (IP) packet routing in the Internet, MPLS tags packets with a 32 bit wide label based on which forwarding is then performed in intermediate routers. MPLS operates at an Open Systems Interconnection (OSI) layer which is often referred to as Layer 2.5, between the data link and the network layer and MPLS labels are positioned between link layer headers and the headers of the encapsulated packet. The name MPLS refers to its independence from both layer 2 and layer 3 protocols, which makes MPLS an interesting candidate for data forwarding in a heterogeneous wireless back-haul network while enforcing Quality of Service (QoS) and paths computed by a centralized network management component. Label-Switched Paths (LSPs) are usually set up and managed using RSVP-TE[1].

The above mentioned protocols are mainly targeted for wired or wireless operator networks where link properties are usually constant and the changing traffic patterns are the main source of dynamic network state changes. acWiBack needs to address an additional source of potentially frequent state changes introduced by the more volatile nature of wireless technologies such as IEEE 802.11. WiBack utilizes a wireless cell resource model to account for link quality fluctuations as well as the MAC layer overhead introduced by shared-medium technologies. When computing new LSPs this model is deployed by the centralized path computation components mostly located at the gateways nodes, which are providing the connection to the operator's core network. For example, typical Voice-over-IP (VoIP) flows with their rather small packets will block larger amounts of cell resources on typical Enhanced Distributed Coordination Access (EDCA) WLAN links due to the overhead of the contention based MAC layer.

As shown in [7], receiver-side wireless link monitoring is a crucial component to monitor WiBack links. For each link triggers are installed at the receiving node which inform the gateway node if the performance drops below a certain threshold so that the link can no longer carry the admitted QoS traffic. In such a case the affected LSPs will be re-routed onto backup paths.

While operator networks require engineers for planning and initial configuration, WiBack utilizes self-management functionality such as self-description, self-configuration and self-healing to minimize the need for technicians. This functionality is provided by the TMF which is implemented at each mesh node. The main TMF process is executed at the centralized gateway node detects and joins mesh nodes in a ring-based approach where direct neighbors are joined first, followed by two-hop neighbors, then three-hop neighbors and so forth. Upon detection and registration of a new mesh node its radio interfaces are configured to match the TMF's optimization criterion, i.e. highest throughput or highest robustness. Once the radio interfaces of the new node have been configured and links have been established with neighboring mesh nodes those links are being made available to the path computation module which may allocate resource and place LSPs onto them.

2.4 GSM Nano-Cells and OpenBTS

A typical GSM setup requires a hierarchy of components that have to be available in order to operate and manage the network, e.g. Home Location Register (HLR) or Mobile-services Switching Centre (MSC). For the designated deployment scenario this has two major drawbacks: First, the required Hard- and Software is very cost-extensive which makes a deployment of a regular GSM network unappealing for operators due to the expected small number of customers per cell. Second, all components of the typical GSM architecture have to be available at all time. Thus, a failure of a single component can lead to a complete network failure. Particularly if nodes have no constant power supply but are only equipped with a solar cell leading to a higher failure rate this becomes much more important. We therefore propose in our approach to carry the voice traffic over a WiBack network as described in section 2 and to terminate the GSM based communication right in the access point and use SIP or IAX2 to carry the voice data to its destination or a connection point to the Public Switched Telephone Network (PSTN).

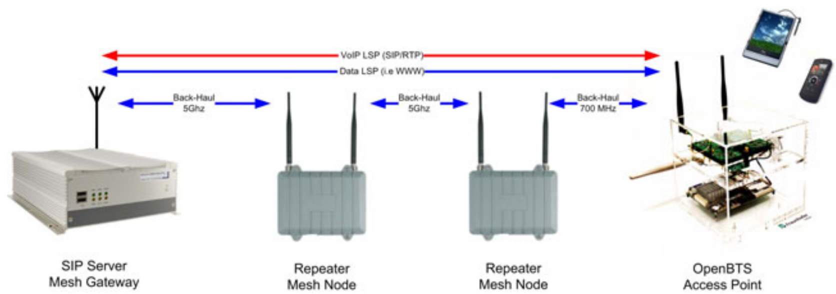

Fig. 2. Integration of an OpenBTS-based GSM cell into a WiBack Access Point

Our actual setup as depicted in Figure 2 makes use of the OpenBTS[1] project software in combination with the Universal Software Radio Peripheral (USRP)[2]. This gives us the advantage of a GSM to SIP adaption directly at the access point without the need of any further GSM-related software components anywhere else in the architecture. The voice traffic is converted in the AP and transported via a dedicated VoIP LSP to its destination.

Due to lower costs and the flexibility of WiBack this architecture makes it easy to provide a higher reliability of the network by providing backup links or redundancy in terms of components. Apart from that, even if a component fails in contrast to a typical GSM network communication in other parts of the network might be still available. For example, if the back-haul connection to a particular village breaks down VoIP/GSM calls within the village are still possible.

[1] http://www.openbts.org
[2] http://www.ettus.com/products

It should also be noted that the proposed architecture also allows for making VoIP calls with a normal computer like the OLPC laptop using a Soft-phone and the Wifi access network. The back-haul network transports both calls equally using the VoIP LSP.

Additionally the architecture allows for transparently changing of the actual transport protocol of the VoIP traffic. For example, in order to optimize the link utilization within the mesh instead of SIP the IAX2 protocol can be used which is able to aggregate the packets of multiple calls via a trunk connection, which leads to a larger packet size and therefore to a lower MAC overhead.

The OpenBTS software in combination with the USRP implements a so called nano-cell which has the advantage of low power consumption and low costs. The trade-off is the lower transmission power resulting in a smaller coverage area in comparison to a standard macro-cell, which is in-line with our target scenario which attempts to cover hot spots, i.e. smaller villages, but not the deserted areas between them.

Another approach would be to use commercial nano-cells like the ip.access nano-bts[5]. The advantage is the availability of ready to use devices. Currently the nano-bts is only supported by the OpenBSC project which tries to implement the ABIS1 protocol and all mandatory parts of the GSM architecture. This would increase the complexity of our mesh access points since they would be required to provide GSM functionality that is not required by our approach.

Both approaches allow building a minimal mesh node which only consists of a WLAN access point and a GSM access point which can be run on the same physical machine. A low power CPU like the Intel Atom is able to handle running the operation system, the OpenBTS module and the WiBack components.

As mentioned before nano-cells have a much smaller energy footprint in comparison with macro cells. Beneath the smaller energy consumption resulting of the smaller TX / RX amplification power can be saved by adapting the amplifier in times of low load which is more likely on a smaller cell. Additionally, lower power consumption leads to lower demand on cooling which again results in a lower power consumption of the entire system.

A standard GSM setup includes an Uninterruptible Power Supply (UPS) to power the base station in case of loss of power. An UPS setup consumes about 15% of the entire power required by the base station. Powering the nano-cell with solar and wind energy necessarily leads to a battery setup in order to buffer the energy which makes an additional UPS setup needless.

A usual macro-cell consumes between 1400W and 3700W depending on the number of carrier frequency used in the cell. A nano-cells instead consumes only between 30W and 60W depending on amplification and number of used carrier frequencies which makes a solar power supply realistic in particular in Africa due to the high solar irradiance.

3 Evaluation

In this section we evaluate the performance of our solution in an out-door testbed. First, we analyze the implemented scenario. Then we evaluate the possible impact of background traffic on prioritized VoIP flows and show that our traffic class based queueing can enforce the proper QoS assurance over five wireless hops.

3.1 Test Scenario

The test scenario, see Figure 3, has been setup using our wireless mesh testbed at the Fraunhofer Campus in Sankt Augustin, Germany[8]. The focus of this scenario is the evaluation of a WiBack network with OpenBTS-based access points for deployment in unconnected rural areas. The test setup consists of six mesh nodes, a gateway node, four forwarding nodes, as well as an access point node, which also incorporates the OpenBTS GSM module. The links between the nodes are implemented using standard IEEE 802.11 hardware in EDCA mode operating in the 5 GHz and the 700 MHz spectrum. The distances between between the nodes are between 20m and 50m, with the 700 MHz link being a None Line of Sight (NLOS) link. As depicted in Figure 3, the links are operating at different data rates. We have chosen a combination of sub-optimal real-world links to best match a realistic deployment scenario.

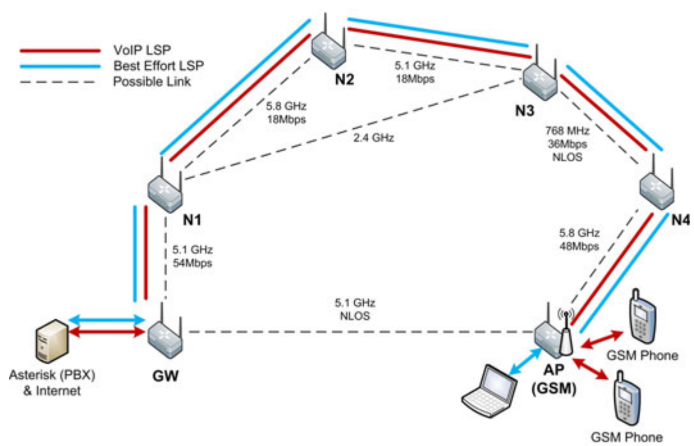

Fig. 3. Traffic is forwarded over four 5GHz and one 768 MHz WLAN Links

Our implementation is based on our high-performance C++ Simple and Extensible Network Framework (SENF)[5] which heavily utilizes boost[6] and modern C++ concepts. The MPLS forwarding function includes a monitoring component which allows us to examine the bandwidth, loss and delay figures per LSP. The figures obtained from this monitoring module will be used in the following sections.

3.2 Evaluation of the Standard Configuration

In the standard configuration, two separate LSP pairs have been configured between the GW and the AP node, one for the VoIP traffic and one for *best effort* traffic, see Figure 3. The Asterisk PBX is located behind the GW node and communicates with the OpenBTS component, which is located at the AP, via the VoIP LSP using SIP/RTP. No traffic aggregation is performed, hence each VoIP packet is sent independently.

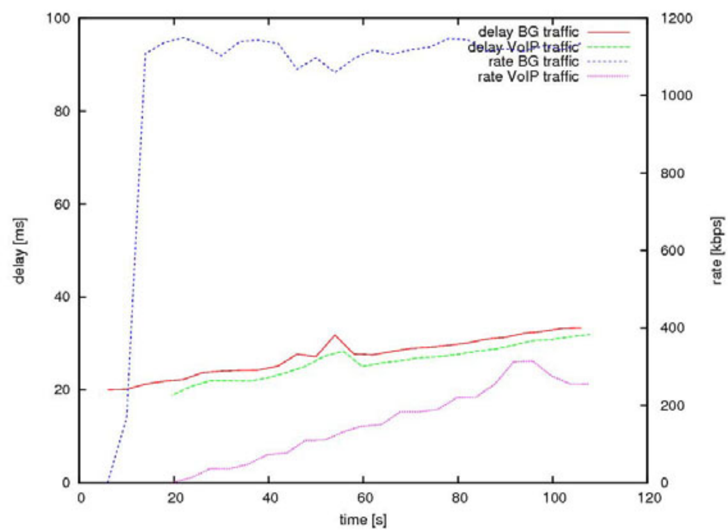

Fig. 4. Bandwidth and delay over an increasing number of phone calls

For this measurement we have loaded the best effort LSP with roughly 1100 kbps of Internet Control Message Protocol (ICMP) traffic. Then, approximately every ten seconds, we have established a new phone call using mobile phones. Figure 4 depicts the measured results on the upstream LSPs from the AP to the GW. The end-to-end latency on both LSPs increases linearly with the increasing load but remains below an acceptable limit for voice calls. No packet loss was observed on either LSP. Hence, we can show that, on not overloaded links, VoIP and best effort traffic can be carried in parallel.

3.3 Loaded Links and DiffServ

In this measurement we evaluated the performance of our architecture under highly loaded link conditions in order to verify that the forwarding function prioritizes the VoIP calls to still provide the committed QoS handling.

To simulate random background traffic, the *best effort* LSP was loaded with traffic generated by parallel *flood pings* with a packet size of 64, 128, 256, 512,

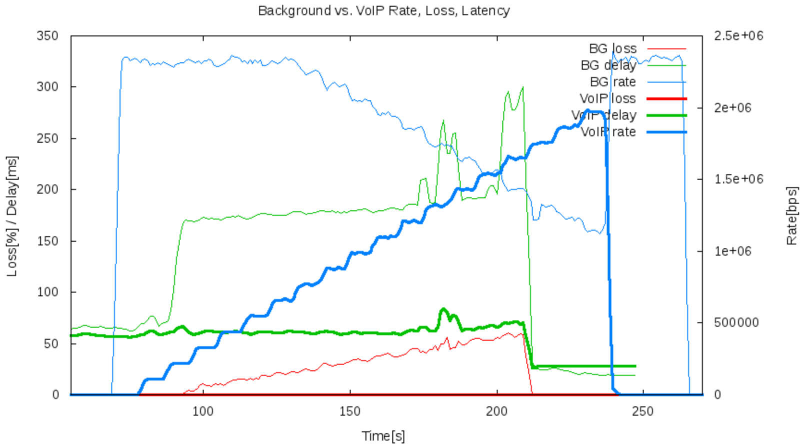

Fig. 5. Bandwidth, delay and loss of the *best effort* and VoIP LSPs under high load

1024 and 1450 bytes, respectively. As depicted in Figure 5, the accumulated background traffic mix added up to roughly 2.3Mbps. Every ten seconds an additional 64kbps VoIP call was added to the prioritized VoIP LSP, up to a maximum of 18 calls. Then all VoIP calls were terminated at time t=240s.

The thick lines in the figure, represent the data of the VoIP flows, while the thin lines represent the best efforts flow's data. It can be observed that initially the background traffic is carried smoothly across the mesh. With an increasing amount of VoIP flows, the bandwidth (blue) of the best effort flow decreases while its loss rate (red) and delay (green) increase accordingly. The VoIP LSP does not experience any increase of delay or noticeable loss.

4 Conclusion and Future Work

We have presented our solution to integrate a GSM nano-cell into WiBack, our meshed wireless back-haul network architecture. Using empirical measurements in our testbed we have shown that the VoIP traffic can be forwarded along a path consisting of five IEEE 802.11 based links without any major delay or loss. Even under high load situations, prioritized VoIP traffic was forwarded smoothly without any noticeable increase of loss or delay, well within the committed QoS assurances.

Future work will focus on the evaluation of trunking VoIP calls between the AP and the GW in order to lower the channel resource utilization overhead caused by the rather small VoIP packet on 802.11 links. Furthermore, we plan to extend to multimedia capability of our architecture by integration multicast-based services to support, for example, emergency paging or community radios.

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