Evolution of cdma2000 cellular networks: Multi-carrier EV-DO

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***Abstract* – The evolution of cdma2000 1xEV-DO systems to multi-carrier EV-DO (supported by 1xEV-DO Revision B) is discussed in this paper. Multi-carrier EV-DO offers a backward compatible upgrade to leverage existing 1xEV-DO networks and terminals. It allows a software upgrade to multi-carrier EV-DO using 1xEV-DO Revision A base station hardware. Multi-carrier operation achieves higher efficiencies relative to single-carrier by exploiting channel frequency selectivity, improved transmit efficiencies on the reverse link, and adaptive load balancing across carriers. Multi-carrier EV-DO enables very high speed download, high resolution video telephony and improved user experience with concurrent applications. The sources of higher efficiency are discussed in detail in this paper. It also enables hybrid frequency re-use deployment scenarios that enable spectrally efficient operation and significant improvement in edge coverage performance with HW efficient implementations. The evolved wider bandwidth systems (up to 20 MHz) based on Multi-carrier EV-DO offer operators a cost-effective solution that competes favorably with other technologies.**

Keywords: cdma2000, 1xEV-DO, IS-856, 1xEV-DO Revision A, 1xEV-DO Revision B, multi-carrier EV-DO

I. INTRODUCTION

Multi-carrier EV-DO is backward compatible with 1xEV-DO Revision A systems and protects operator and end-user investments in infrastructure and devices. While newer terminals are required for multi-carrier operation, single-carrier terminals based on 1xEV-DO Release 0 or 1xEV-DO Revision A can operate on evolved EV-DO networks that support multi-carrier operation. In order to offer end users richer services and improved user experience while lowering operator cost per bit, the 3GPP2 community is developing a standard – 1xEV-DO Revision B – to support multi-carrier EV-DO with expected publication in the first quarter of 2006. Multi-carrier EV-DO specifies up to a 20 MHz wide system with each carrier 1.25 MHz wide and terminals supporting one or more carriers. Operators can deliver Multi-carrier EV-DO based services via software upgrade to 1xEV-DO Revision A channel cards. Multi-carrier devices may operate in a single-carrier mode with 1x (IS-2000) or 1xEV-DO or a multi-carrier mode of operation with two or more EV-DO Revision A carriers. Multi-carrier EV-DO devices may support non-contiguous CDMA channel operation to maximize gains due to channel frequency selectivity and load balancing across carriers.

The fundamental concepts in single-carrier 1xEV-DO systems are discussed in detail in [1] – [8]. Section II discusses fundamental multi-carrier EV-DO concepts and Section III presents the operator and end-user benefits of multi-carrier EV-DO. We present some performance data in Section IV and multi-carrier EV-DO deployment scenarios in Section V followed by a summary in Section VI.

II. FUNDAMENTAL CONCEPTS

Fundamental concepts introduced in Multi-carrier EV-DO are:

1. Channel Aggregation via Multi-link Radio Link Protocol (ML-RLP)
2. Set Management and adaptive server selection
3. Symmetric and Asymmetric modes of operation
4. Multi-carrier Reverse Link MAC
5. Adaptive Load balancing
6. Flexible duplex carrier assignment

A. *Channel Aggregation*

The Radio Link Protocol (or RLP) is an ARQ protocol that reduces the error rate at the physical and MAC layer and provides a lower error rate to higher layers in the protocol stack. Channel aggregation at the RLP[1] layer, called multi-link RLP, allows achieving higher peak data rates utilizing multiple carriers on the forward link using 1xEV-DO-Revision A channel cards. Multi-link RLP is required when a terminal is assigned carriers on channel cards that do not communicate with each other and operate an independent scheduler.

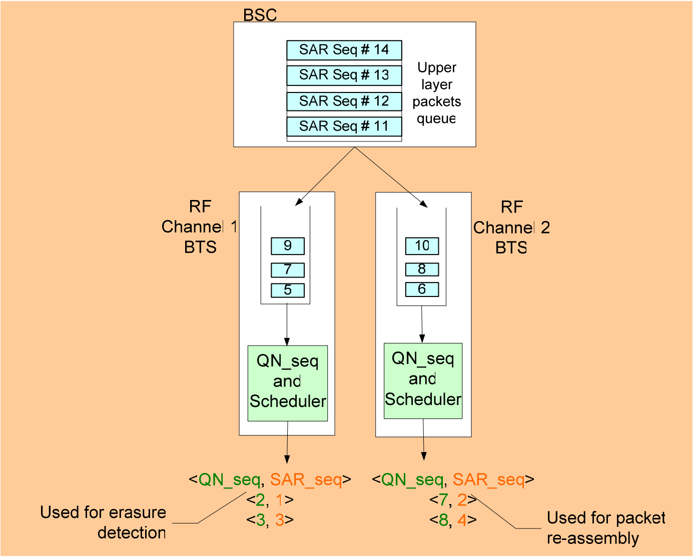

Figure 1. Multi-link RLP operation

As illustrated in Figure 1, the base station controller (BSC) sends distinct packets to each of the assigned carriers (channel cards). The base station transceiver (BTS) builds the packets and adds Quick NAK (QN) sequence numbers to the Segmentation and Re-assembly (SAR). Using the Segmentation and Re-assembly (SAR) sequence numbers, packets transmitted by a given channel card appear to have holes in sequence number space. In Figure 1 a terminal is assigned two carriers, one on each channel card. If this terminal relies on the SAR sequence numbers for detection of the erased RLP packets, it would generate NAK (negative acknowledgements) as soon as it detects a hole in the SAR sequence number space. For example,

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[1] A detailed discussion of the RLP protocol used in 1xEV-DO systems can be found in [1]

if the terminal receives SAR sequence # 1 followed by SAR sequence # 3 from carrier 1, the terminal would interpret that as the RLP packet with SAR sequence #2 has been erased. However, the RLP packet with SAR sequence #2 may be in the queue associated with forward link carrier 2 and has not been transmitted yet. Therefore, the SAR sequence number cannot be relied upon for detection of the erased RLP packets. Multi-link RLP therefore introduces a Quick NAK (QN) sequence number, in addition to the SAR sequence number, which is added by each link (or channel card). The terminal uses the QN sequence number to detect holes in QN sequence number space on each individual link and the SAR sequence number to re-assemble packets received on the separate links as shown in Figure 1. The SAR sequence number would be used by the terminal for re-assembly of the RLP packets that are received from the multiple forward link carriers.

In the example shown, contiguous QN sequence numbers received from each channel card indicate to the terminal that there are no erasures on each link, and re-assembly using the SAR sequence numbers allows multi-link RLP to deliver packets in order to the higher layers. Non-contiguous QN sequence numbers indicate link erasures which are reported using RLP NAKs by the access terminal. Since the QN sequence number is not used for re-transmissions, its length is required to be long enough to avoid wrap-around of the QN sequence numbers during a burst of errors on a given carrier. The length of the SAR sequence number is required to be long enough to avoid wrap-around during a burst of errors across carriers, and to allow for the maximum skew in sequence numbers across different links Since RLP provides a single round of re-transmission, the re-transmitted RLP packets do not need to carry the QN sequence number. It should be noted that Multi-link RLP only necessary on the forward link and is not required when a single scheduler is responsible for scheduling transmission of packets across multiple carries. From the perspective of the single-scheduler that can scheduler packet transmission across carriers the additional carriers are analogous to additional interlaces on the forward link.

B. Set Management and Adaptive Server selection

A pilot in Multi-carrier EV-DO is specified by a <PN Offset, CDMA channel> ordered pair. Pilot Groups are formed so that the terminal does not send multiple reports for pilots that have the same spatial coverage. Two pilots are defined to belong to the same Pilot Group if both the PN offset and the GroupID associated with the two pilots are the same. A single pilot is used as a representative for the group and the access terminal reports the pilot strength of exactly one pilot from each Pilot Group in the Active Set and Candidate Set.

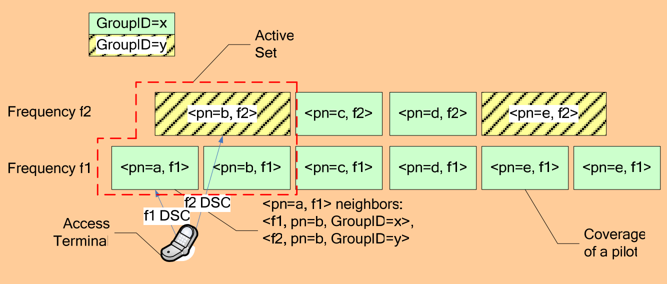

Figure 2. Pilot GroupID assignment/coverage and DSC pointing

The Active Set refers to the current <PN Offset, CDMA channel> ordered pairs from which the access terminal can request data transmission on the forward link. The Candidate Set refers to sectors that are being received with sufficient strength that they could be demodulated but are not yet included in the active set. The Neighbor Set refers to the set of sectors that are candidates for handoff and cover the geographical area near the access terminal. The Active Set may include more than one pilot from the same Pilot Group. However, none of the members of the Neighbor and Candidate Sets belong to the same Pilot Group as that of the pilots in any of the other sets.

Assigning different pilot groups based on coverage allows the access network to receive separate pilot strength reports from the access terminal when the coverage areas of the co-located pilots are different, since the Pilot Group is identified by the <Pilot_PN, GroupID>, the network can use the same Pilot_PN planning for the pilots on different carriers as shown in Figure 2.

The access terminal can take advantage of the expanded coverage of <PN Offset=b, CDMA Channel = f2> relative to that of <PN Offset=b, CDMA Channel = f1>. The coverage of <PN Offset=b, CDMA Channel = f2> is larger due to the reduced adjacent channel interference on f2 as the sector with PN Offset = a does not transmit on CDMA Channel = f2. The access terminal can request data from different cells on different frequencies simultaneously as shown in Figure 2. The Data Source Control Channel (DSC) channel in multi-carrier EV-DO is used to select the desired forward link data source for each forward link carrier. For example, an access terminal can receive data for a delay-tolerant flow from different data sources (i.e. cells) on each forward link frequency if using multi-link RLP with the different channel cards residing on different cells.

C. Symmetric and Asymmetric mode of operation

Multi-carrier EV-DO supports the following three modes of operation

- Symmetric multi-carrier mode
- Basic asymmetric multi-carrier mode
- Enhanced asymmetric multi-carrier mode

In symmetric multi-carrier mode the number of forward CDMA channels is equal to the number of reverse CDMA channels. The feedback channels for each forward CDMA channel are transmitted on a unique reverse CDMA channel using the same user long code sequences on each reverse CDMA channel. The symmetric mode of operation may be used for applications with symmetric data rate requirements on the forward and reverse links. The symmetric multi-carrier mode enables multi-carrier operation using aggregation of 1xEV-DO channel cards. If the access network hardware supports asymmetric mode of operation, terminals would be setup in asymmetric mode for applications such as file download that require more bandwidth on the forward link than the reverse link. Asymmetric mode of operation results in reduced reverse link overhead as the pilot channels for the additional reverse link carriers are not transmitted.

In basic asymmetric multi-carrier mode a single reverse CDMA channel may carry feedback (Data Rate Control (DRC) Channel, Acknowledgement (ACK) channel transmissions, and Data Source Control (DSC) channel transmissions) for more than one forward CDMA channels using unique long codes for each feedback channel. The feedback channel transmissions for the secondary forward link carriers use a distinct long code mask and therefore appear as additional users in the system. These long code masks are derived by modifying the 4 MSBs of the Reverse Traffic Channel long code mask used in 1xEV-DO Revision A. The basic asymmetric mode was designed to be supported with 1xEV-DO Revision A channel cards as the feedback for the secondary forward link carriers appears as additional users on the channel card.

The asymmetric mode of operation is scalable and can support any number of forward carriers for which DRC, ACK, and DSC can be transmitted on the primary reverse carrier. The pilot channel from the primary carrier is used to demodulate the DRC, ACK, and DSC, at the access network, for the secondary carriers. The asymmetric mode of operation is also possible with fewer data carriers on the forward link than the reverse link. For each reverse link carrier, the corresponding forward link is used to transmit power control and ARQ signaling but may not be used for data transmissions. Such operation may be used for terminals uploading large amounts of data.

Enhanced asymmetric multi-carrier mode is similar to the basic asymmetric multi-carrier mode with the exception that feedback channels for up to four forward CDMA channels are transmitted on a single reverse link using the same long code. Therefore, a 16-carrier forward link may be supported using a reverse link carrier with basic asymmetric mode by using 16 unique user long codes or with enhanced asymmetric mode by using 4 unique user long codes. The enhanced asymmetric multi-carrier mode therefore offers the most efficient implementation and can be achieved with more flexible hardware platforms. Further details on the multi-carrier EV-DO modes of operation can be found in [10].

D. Multi-carrier Reverse Traffic Channel MAC

The single-carrier reverse link MAC is described in detail in [4] through [6]. Salient features of the Multi-carrier reverse traffic channel MAC (RTCMAC) are flow to carrier mapping, data policing, efficient reverse link transmission, and reverse link load balancing. In case of single-carrier assignment, a single reverse traffic channel MAC (RTCMAC) bucket per flow accomplishes both flow policing as well as access control in the Traffic-to-Pilot (T2P) power domain. Further details of the 1xEV-DO Revision A RTCMAC can be found in [1]. The flow policing function ensures that average and peak flow data rate is less than or equal to the limit imposed by the access network. The access control function determines the rules that the flow uses for reverse link transmissions.

The reverse link MAC specifies two primary types of flows, fixed allocation flows and elastic flows. Fixed allocation flows (example: delay-sensitive flows) have high priority and are always permitted use of network resources up to specified limit. Elastic allocation flows (example: best effort flows) use excess network resources once the demands of all fixed allocation flows have been met. In case of multi-carrier operation, the flow access control and flow policing functions are separated out for delay-sensitive flows, with similar fixed allocation priority functions[2] for access control across carriers thereby enabling the access terminal to load balance across carriers and exploit multi-user diversity as appropriate. Elastic allocation for delay-tolerant flows does not require a policing function as these flows use available sector capacity following allocation for fixed allocation flows. Therefore, with multi-carrier assignment the number of RTCMAC buckets per flow equals the number of assigned carriers for access control on each carrier which is accomplished by the assigned priority functions in the T2P domain. This per carrier allocation is similar to that used for single-carrier systems and may be the same across all carriers. In addition, fixed allocation flows are assigned a flow policing bucket that performs policing in the data domain. It ensures that the flow (or terminal) cannot abuse the additional allocation in a multi-carrier system. An advantage of this approach is that as the number of carriers assigned to a terminal changes, changes to RTCMAC parameters are not required.

The access terminal attempts to achieve efficient transmission while achieving load balancing by favoring the reverse link carrier, with the least interference for each reverse link packet transmission, if data limited or power limited. In addition, the access terminal achieves improved transmit efficiency for delay-tolerant traffic via the use of multi-carrier transmission which is discussed in the section on benefits of multi-carrier EV-DO.

E. Adaptive Load Balancing

As in single-carrier systems, CDMA channel assignment in multi-carrier EV-DO is performed at the BSC. The channel assignment mechanism minimizes service interruption at the access terminal due to channel assignment. Channel assignment or de-assignment is a co-operative message based allocation between the access network and access terminals in order to achieve load balancing across carriers. Load balancing ensures that the network loading is uniform across carriers. Static load balancing is achieved by assigning each new access terminal to a set of carriers. Due to variable nature of application flows and bursty data sources, static load balancing cannot achieve uniform loading across carriers on shorter time scales. Adaptive load balancing can be achieved via co-operation between the access network and access terminal. The access network assigns carriers to each access terminal based on carrier loading, terminal flow composition, and terminal capabilities. On the forward link the access network can achieve load balancing on a per packet basis. Similar fine load balancing is achieved on the reverse link by per packet carrier selection (of the assigned carriers) by the access terminal. If near uniform load is maintained across carriers, the access network can assign carriers to access terminals in a way that maximizes capacity utilization and spectral efficiency gains. To that extent, the access network can assign all carriers that a terminal can support which permits the terminal to receive packet transmissions on the "best" carrier during the "best" time-slot. On the reverse link, load balancing ensures nearly equal interference on each carrier thereby enabling the terminal to pick the instantaneous "best" carrier for reverse link transmissions on a packet-by-packet basis. The access network may assign lightly loaded carriers to access terminals with higher rate data sources and favor some carriers for power amplifier headroom limited access terminals.

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[2] Different priority functions may be assigned to some of the assigned carriers to aid load balancing across carriers.

The access network can assign carriers at connection setup based on access terminal flow requirements, available power amplifier headroom[3] at the access terminal, and access terminal capability[4]. In addition, the access network can assign or re-allocate carriers as needed during a connection. Carrier assignment and de-assignment are initiated by the access network or access terminal but are determined by the access network with one exception. If an access terminal is power amplifier headroom limited, the access terminal de-assigns the carrier autonomously and then reports the de-assignment to the access network so that the access network can de-allocate resources assigned to the access terminal on that carrier.

Connection setup requires access terminal transmission on the access channel and subsequent connection setup procedures. Assignment of additional reverse link carriers in connected state is performed using the traffic channel. Therefore, it does not require access channel transmission and procedures as in connection setup and leads to lower latencies than connection setup.

F. *Flexible Duplex*

Typical CDMA systems assign forward CDMA channels and reverse CDMA channels that have a fixed spacing as specified by the band class document [10]. Access Terminals are typically designed based on a fixed duplexer spacing. Examples of fixed duplexer spacing and flexible duplexer spacing are shown in Figure 6 where deployment scenarios enabled by flexible duplexing are discussed. With flexible duplex spacing, any reverse CDMA channel from a band class can be coupled with any forward CDMA channel from that band class or with a forward CDMA channel from another band class subject to the capabilities of the access terminal (indicated by session attributes to the network). This also allows using a reverse CDMA channel from a paired spectrum with forward CDMA channels from both the paired spectrum as well as unpaired spectrum providing operators further flexibility in spectrum allocation.

III. BENEFITS OF MULTI-CARRIER EV-DO

Multi-carrier EV-DO offers both operators and end-users significant benefits over that of single-carrier systems. Some of the benefits of Multi-carrier EV-DO are:

1. Backward compatibility
2. Re-use of existing infrastructure hardware, lower development cost, and rapid time to market
3. Higher peak data rates, reduced latency and improved support for QoS sensitive applications
4. Improved transmit efficiency (reverse link)
5. Higher spectral efficiency via exploiting frequency selective fading across carriers.
6. Adaptive Load balancing across carriers
7. Alternate deployment scenarios due to use of flexible duplex assignment

A. *Improved Transmit Efficiency (Reverse Link)*

The 1xEV-DO Revision A reverse link supports data rates from 4.8 kbps to 1.8Mbps and permits achieving different latency targets which is described in detail in [1]. 1xEV-DO Revision A supports termination targets[5] of 4, 8, 12, or 16-slots. The longer termination targets are used for delay-tolerant traffic and the shorter termination targets are used for delay-sensitive traffic. Delay tolerant traffic typically uses a 16-slot termination target called the High Capacity (or HiCap) mode while the delay-sensitive traffic typically uses an 8-slot termination target called the Low Latency (or LoLat) mode. Transmissions in the Low Latency mode trade-off spectral efficiency for delay.

In order to achieve data rates at the high end, a single carrier access terminal transmits using the Low Latency (or LoLat) mode of transmission. For example, a single carrier terminal can achieve 1.8Mbps by transmitting a 12288 bit physical layer payload with a termination target of 4-slots. If the lower latency is not required, a multi-carrier capable terminal can achieve higher data rates without trading off spectral efficiency for delay. By transmitting a 12288 bit payload on 3-carriers with a termination target of 16-slots, a multi-carrier capable access terminal can achieve a data rate (summed over all reverse link carriers) in excess of 1.8Mbps. The nominal data rate for 12288 bit payloads over 16-slots is 460.8 kbps, but a higher effective data rate is achieved by early termination due to physical layer H-ARQ. A multi-carrier terminal can therefore achieve higher spectral efficiency than a single-carrier terminal for delay-tolerant traffic.

B. *Improved spectral efficiency due to channel frequency selectivity*

Single-carrier systems such as 1xEV-DO exploit multi-user diversity in the time domain. Multi-carrier systems such as EV-DO enable exploiting multi-user diversity both in the time and frequency domains thereby achieving higher spectral efficiencies than single-carrier systems. The gains due to multi-user diversity in the frequency domain are a function of the inter-frequency channel correlation.

In order to evaluate the inter-frequency channel correlation between adjacent CDMA channels, field tests were conducted on test EV-DO system using three adjacent 1xEV-DO Release 0 carriers in an embedded[6] sector. A time-frequency plot of the observed Signal to Interference and Noise Ratio (SINR) is shown in Figure 3. The X-axis shows the time in half-slots[7], the Y-axis shows adjacent CDMA frequencies, and the Z-axis shows the two-dimensional SINR in time and frequency. We see that the rich fading channel in time and frequency can be exploited to achieve significant gains in spectral efficiency due to multi-user diversity. Data analysis from these field tests showed a channel correlation between adjacent CDMA channels of ~65% which decreases with increasing channel spacing (60% for CDMA channels separated by one CDMA channel). Since sufficient channel de-correlation is achieved within 5MHz of channel bandwidth, multi-carrier terminals that support three

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[3] The terminal indicates its available PA headroom as the total available transmit power less the sum of the pilot channel transmit powers when requesting additional carriers or when polled by the access network

[4] Access Terminal capability is indicated to the access network using the Capability Discovery Protocol and would be used to indicate number of carriers supported by the access terminal as well as maximum inter-carrier spacing.

[5] Termination target is defined as the number of slots of transmission required to achieve a desired packet error rate, typically 1%.

[6] An embedded sector is a sector surrounded by other sectors resulting in other-sector interference and emulates a real-world deployment.

[7] A time-slot in 1xEV-DO is 1.666 ms.

carriers would be able to exploit most of the channel frequency selectivity.

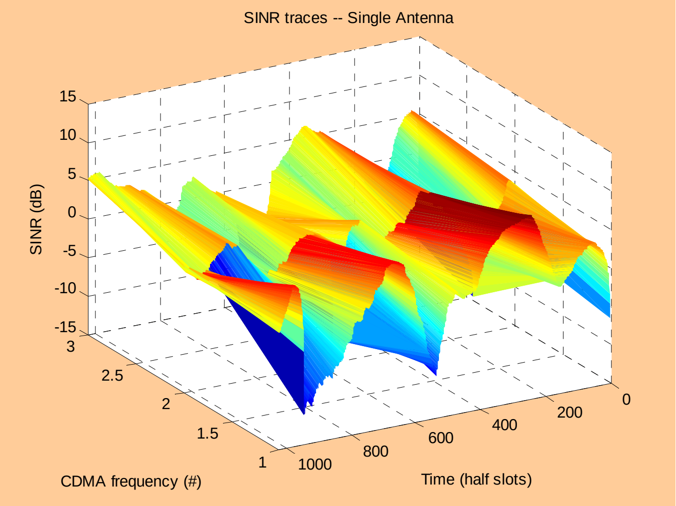

Figure 3. Example forward link SINR trace in time and frequency domain for multi-carrier EV-DO

IV. PERFORMANCE

A. Forward Link

Multi-carrier EV-DO offers forward link performance enhancements due to channel frequency selectivity and adaptive load balancing. In this section we show the performance gains due to exploiting Channel frequency selectivity based on a simulation framework defined by the 3GPP2 evaluation methodology [2]. Support for multi-carrier is added to the single carrier evaluation methodology. The channel models are augmented for multi-carrier assuming the same long-term fading across carriers in a multi-carrier assignment and independent short-term fading. These results therefore present an upper bound for the capacity gains possible due to channel frequency selectivity. In order to quantify the gains due to channel frequency selectivity for multi-carrier EV-DO, we use a proportional-fair (P-fair) scheduler, the equal grade-of-service (EGoS) scheduler, and the Quality-of-Service scheduler modified to support multi-carrier operation.

In 1xEV-DO the access terminal reports the channel state information to the “best” forward link serving sector for each time-slot using the DRC (Data Rate Channel) indicator. We therefore define $\mathrm{DRC}_{i,j}(n)$ as the channel state information from access network to access terminal ‘i’ on CDMA channel ‘j’ in time-slot ‘n’, $\mathrm{E}\left[\mathrm{DRC}_{i,j}\right]$ is the average DRC reported by the access terminal. We also define $d_i(n)$ as the delay experienced by the packets for user ‘i’ at time-slot ‘n’, and $R_i(n)$ is the filtered average of the served throughput for a user. The filter time-constant of the $R_i(n)$ computation controls the multi-user diversity gain in single-carrier systems with larger values producing higher multi-user diversity gains and smaller values achieving better latencies.

The proportional fair scheduler attempts to maximize the following metric for each slot ‘n’: On each carrier ‘j’ transmit to the user ‘i’ that maximizes the metric $\frac{\mathrm{DRC}_{i,j}(n)}{R_i(n)}$. The Equal-Grade-of-Service scheduler maximizes the metric $\frac{\mathrm{DRC}_{i,j}(n)}{\mathrm{E}[\mathrm{DRC}_{i,j}]}\cdot\frac{1}{R_i(n)}$ and the QoS scheduler maximizes the metric $\frac{\mathrm{DRC}_{i,j}(n)}{\mathrm{E}[\mathrm{DRC}_{i,j}]}\cdot\frac{d_i}{R_i(n)}$. The analysis presented in this paper focuses on channel model A (1-path Rayleigh fading channel at 3 km/h) which is the most challenging channel for meeting QoS requirements. The simulations are based on 16 access terminals per carrier per sector with the multi-carrier simulations based on 3-carriers assigned per access terminal.

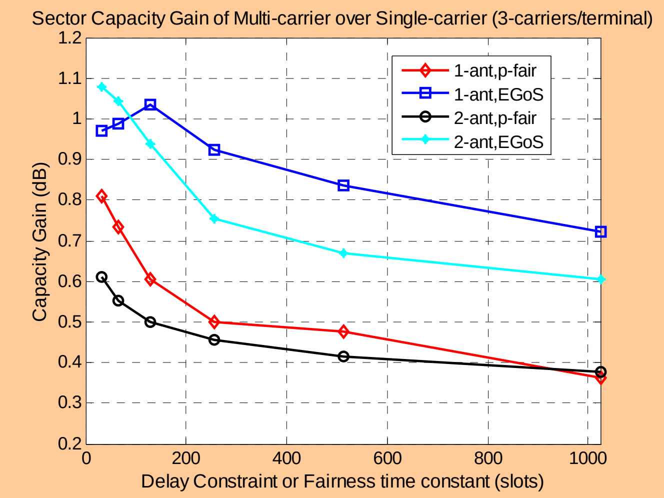

Figure 4. Capacity gains due to channel frequency selectivity for multi-carrier over single-carrier (16-terminal/sector, 3-carrier/terminal)

Figure 4 shows the gains in sector throughput of a multi-carrier forward link over that of a single-carrier forward link with the same number of receive antennas. We see that for larger values of delay constraints (i.e. the fairness time constant), the gains with a multi-carrier system are lower and increase for smaller values of delay constraint. With larger values of delay constraint (applicable only for delay-tolerant traffic), the access network can delay packet transmissions in order to exploit multi-user diversity (i.e., serve users at or near their channel peaks) in the time-domain, which limits the multi-user diversity gains of a multi-carrier system in the frequency domain to moderate values. Single-carrier systems offer improved latency performance for delay-sensitive users at the expense of multi-user diversity (lower spectral efficiency).

With the use of multi-carrier systems, multi-user diversity can be exploited in both the time and frequency domains and therefore spectral efficiency gains are possible while meeting stringent delay constraints for QoS sensitive applications. Figure 4 also shows higher gains with equal Grade-of-Service (GoS) schedulers relative to proportional-fair schedulers. Since equal GoS schedulers try to achieve equal throughput across all users, users in poor channel conditions are allocated resources a larger fraction of time to achieve the same performance as users in better channel conditions which reduces the gains due to multi-user diversity for single carrier systems. A multi-carrier equal GoS forward link scheduler improves performance of all users as it is better able to match transmit time slots and frequency channels with channel peaks experienced by each access terminal in the time and frequency domain respectively.

B. *Reverse Link*

Multi-carrier EV-DO offers reverse link performance enhancements primarily due to adaptive load balancing and efficient transmission of delay-tolerant traffic.

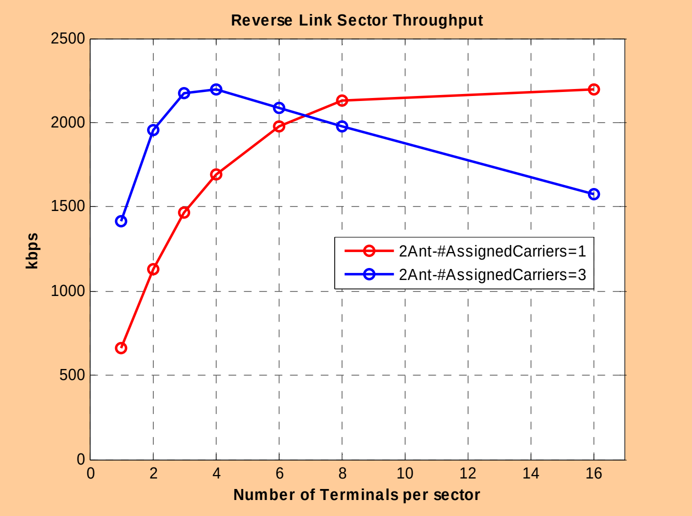

Figure 5. Reverse Link Sector Capacity for multi-carrier operation

Figure 5 shows the reverse link sector capacity as a function of number of users per carrier with a 2-antenna receiver at the base station. Sparsely loaded sectors with single carrier terminals may not be able to utilize available capacity as terminals at cell edge are link budget limited and terminals closer to the center of the cell are limited by the number of carriers on which they can transmit. In sparsely loaded networks we see that the sector capacity is increased due to terminals close to the center of the cell transmitting on multiple carriers and using up available capacity. As the number of users per carrier increases we see that the reverse link interference due to overhead channels results in a capacity degradation. Therefore, carrier allocation algorithms would assign users multiple carriers when the reverse link is sparsely loaded.

Terminals close to the base station can benefit from the higher data rates due to multi-carrier operation and as the distance (or path loss) from the base station increases the terminal data rate decreases. Since multi-carrier operation on the reverse link improves the reverse link transmit efficiency at high data rates multi-carrier usage at moderate distances from the base station allows the access terminal to continue operating using the spectrally efficient high capacity mode. This results in coverage improvements when transmitting at higher data rates.

V. DEPLOYMENT SCENARIOS

Two likely Multi-carrier EV-DO deployment scenarios are as follows:

- Overlay (Additional carriers added to existing 1xEV-DO Revision A single-carrier deployments)
- Hybrid frequency reuse (Frequency re-use of 3 on additional forward link carriers along with frequency-reuse of 1 on one or more forward link carriers and Frequency re-use of 1 on all reverse link carriers)

In this section we represent frequency re-use of 1 by K=1 and represent frequency re-use of 3 by K=3. $(K=1)^2$ implies 2-carriers with K=1 and $(K=1)^3$ implies 3-carriers with K=1. 2-carrier operation is represented by 2x and 3-carrier operation is represented by 3x.

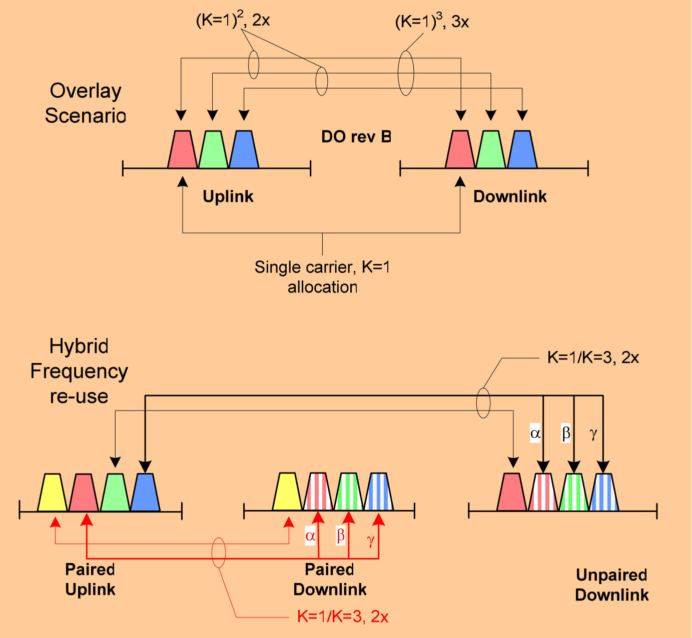

Figure 6. Multi-carrier EV-DO deployment scenarios

Operators can add supplemental 1xEV-DO carriers in addition to existing 1xEV-DO Revision A carriers as shown in Figure 6 (Overlay Scenario) to achieve the benefits mentioned above.

Hybrid frequency re-use is defined as the use of different frequency re-use for distinct sets of CDMA channels. For the example shown in Figure 6 (Hybrid Frequency reuse), we use K=1 for one or more CDMA channels along with K=3 for other CDMA channels. Multi-carrier EV-DO enables hybrid frequency re-use deployments. The use of K=1 allows legacy terminal operation and allows terminals using the K=3 carriers to perform active set management using the K = 1 carrier as in the overlay deployment scenario. The configuration shown in Figure 6 (Hybrid Frequency reuse) is enabled by flexible duplex and multi-carrier operation. α,β and γ represent the sectors using the CDMA channel shown. Due to sector based frequency re-use of 3, each sector only transmits one of the three frequencies from each frequency re-use set of 3.

In the hybrid frequency re-use scenario shown, four forward and reverse CDMA channels from paired spectrum are used along with four forward CDMA channels from unpaired spectrum. Three carriers from the paired and unpaired spectrum are used on the forward link with K=3 along with one carrier in the paired and unpaired spectrum with K =1. The reverse CDMA channels use K=1 and are coupled with the forward CDMA channels from the paired spectrum or with the forward CDMA channels from the unpaired spectrum. We illustrate two-carrier operation where one carrier uses K=1 and the other carrier uses K=3. K=1 is used on the reverse link to maintain seamless operation and exploit benefits of soft-handoff.

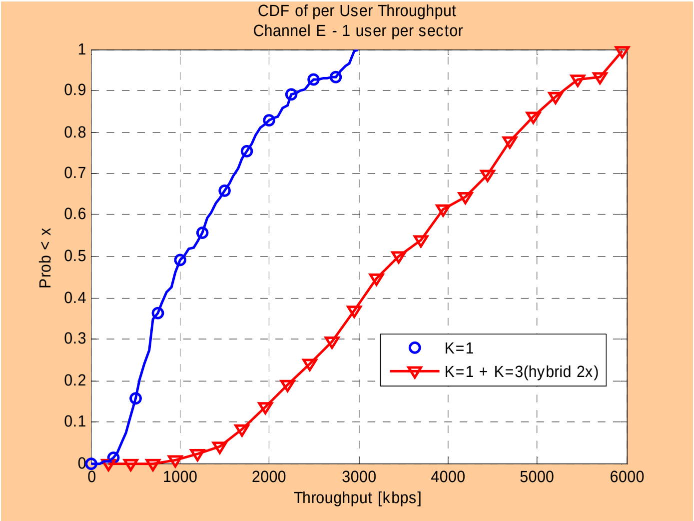

Figure 7. CDF of single user throughput (K=1 vs. K=1 + K=3, hybrid frequency reuse)

Hybrid frequency re-use with flexible duplexing is spectrally efficient based on an EGoS criterion as joint scheduling across carriers efficiently utilizes the carrier with K=1 for users that do not benefit from the carrier with K=3. Due to sector based K=3, the 4 forward CDMA channels can be supported using the same hardware required for 2 forward CDMA channels using K=1. K=3 on the forward link results in an improved SINR distribution especially for users at cell edge resulting in substantial improvement in the single user throughput as shown in Figure 7. This data is based on network layout consistent with the 3GPP2 evaluation framework [2]. In Figure 7, with K=1 on one carrier with K=3 for another carrier for a hybrid frequency re-use, 2x deployment, we see that the cell edge users observe a four-fold increase in throughput, and the peak data rate increased of a factor of two. This shows that an EGoS throughput increase of roughly a factor of 4 (relative to the single carrier K=1 case) on the forward link can be achieved via the use of four CDMA channels (K=1 for one carrier and K=3 for three carriers) with half the hardware required if using K=1.

VI. SUMMARY AND CONCLUSIONS

Multi-carrier EV-DO offers a backward compatible upgrade to 1xEV-DO systems to achieve lower cost per bit and higher spectral efficiencies. In addition to higher peak data rates and lower latencies further gains can be achieved due to reverse link transmit efficiency for delay-tolerant flows, spectral efficiency (due to frequency selective fading), and adaptive load balancing. It also enables hybrid frequency re-use deployments in addition to overlays via the use of forward link frequency re-use and flexible duplex channel assignments.

VII. REFERENCES

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